Physics of right-handed neutrinos
-- tests of the seesaw mechanism --

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基研研究会　素粒子物理学の進展２０１５@YITP

TA, Tsuyuki arXiv:1508.04937
TA, Tsuyuki arXiv:1509.02678

@YITP, Kyoto　(2015/09/16)

Plan of this talk

- Introduction
  - the seesaw mechanism for neutrino masses

- Limits on heavy neutral leptons in the seesaw mechanism
  - neutrino masses, cosmology, direct/indirect searches

- Lepton number violation in the seesaw mechanism
  - neutrinoless double beta decay
  - $e^- e^- \to W^- W^-$ (“*inverse neutrinoless double beta decay*”)

- Perturbativity in the seesaw mechanism

- Summary

Introduction

Origin of neutrino masses

- Neutrino mass scales
  - Atmospheric: $\Delta m^2_{\rm atm} \simeq 2.4 \times 10^{-3} {\rm eV}^2$
  - Solar : $\Delta m^2_{\rm sol} \simeq 7.5 \times 10^{-5} {\rm eV}^2$

$\Rightarrow$ **Clear signal for new physics beyond the SM !**

- Important questions:
  - **What is the origin of neutrino masses?**
  - **What are the implications to other physics?**
  - **How do we test it experimentally?**

RH Neutrinos ν_R and Seesaw Mechanism

$$\boxed{\delta L = i\overline{\nu_R}\partial_\mu \gamma^\mu \nu_R - F\,\overline{L}\,\nu_R\Phi - \frac{M_M}{2}\overline{\nu_R}\nu_R^c + \text{h.c.}}$$

Minkowski '77
Yanagida '79
Gell-Mann, Ramond, Slansky '79
Glashow '79

- Seesaw mechanism ($M_D = F\langle\Phi\rangle \ll M_M$)

$$-L = \frac{1}{2}(\overline{\nu_L}, \overline{\nu_R^c})\begin{pmatrix} 0 & M_D \\ M_D^T & M_M \end{pmatrix}\begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + h.c = \frac{1}{2}(\overline{\nu}, \overline{N^c})\begin{pmatrix} M_\nu & 0 \\ 0 & M_M \end{pmatrix}\begin{pmatrix} \nu^c \\ N \end{pmatrix} + h.c.$$

$$M_\nu = -M_D^T \frac{1}{M_M} M_D$$

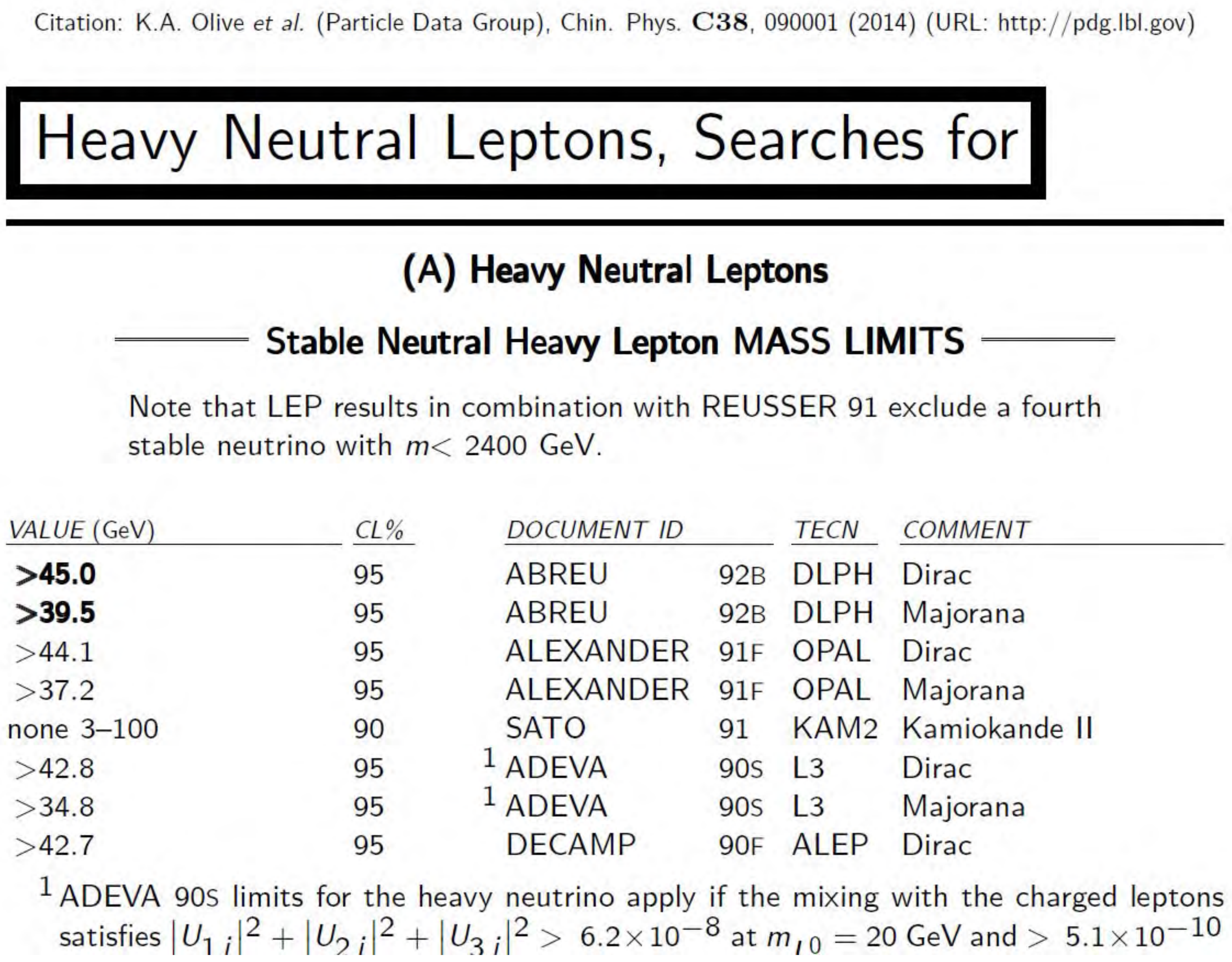
$$U^T M_\nu U = diag(m_1, m_2, m_3)$$

- **Light active neutrinos ν**
  → explain neutrino oscillations
- **Heavy neutral leptons N**
  - Mass M_M
  - Mixing $\Theta = M_D/M_M$

$(N \simeq \nu_R)$

mixing in CC current $\nu_L = U\,\nu + \Theta\, N^c$

Review of Particle Physics



Citation: K.A. Olive *et al.* (Particle Data Group), Chin. Phys. **C38**, 090001 (2014) (URL: http://pdg.lbl.gov)

Heavy Neutral Leptons, Searches for

(A) Heavy Neutral Leptons

Stable Neutral Heavy Lepton MASS LIMITS

Note that LEP results in combination with REUSSER 91 exclude a fourth stable neutrino with $m <$ 2400 GeV.

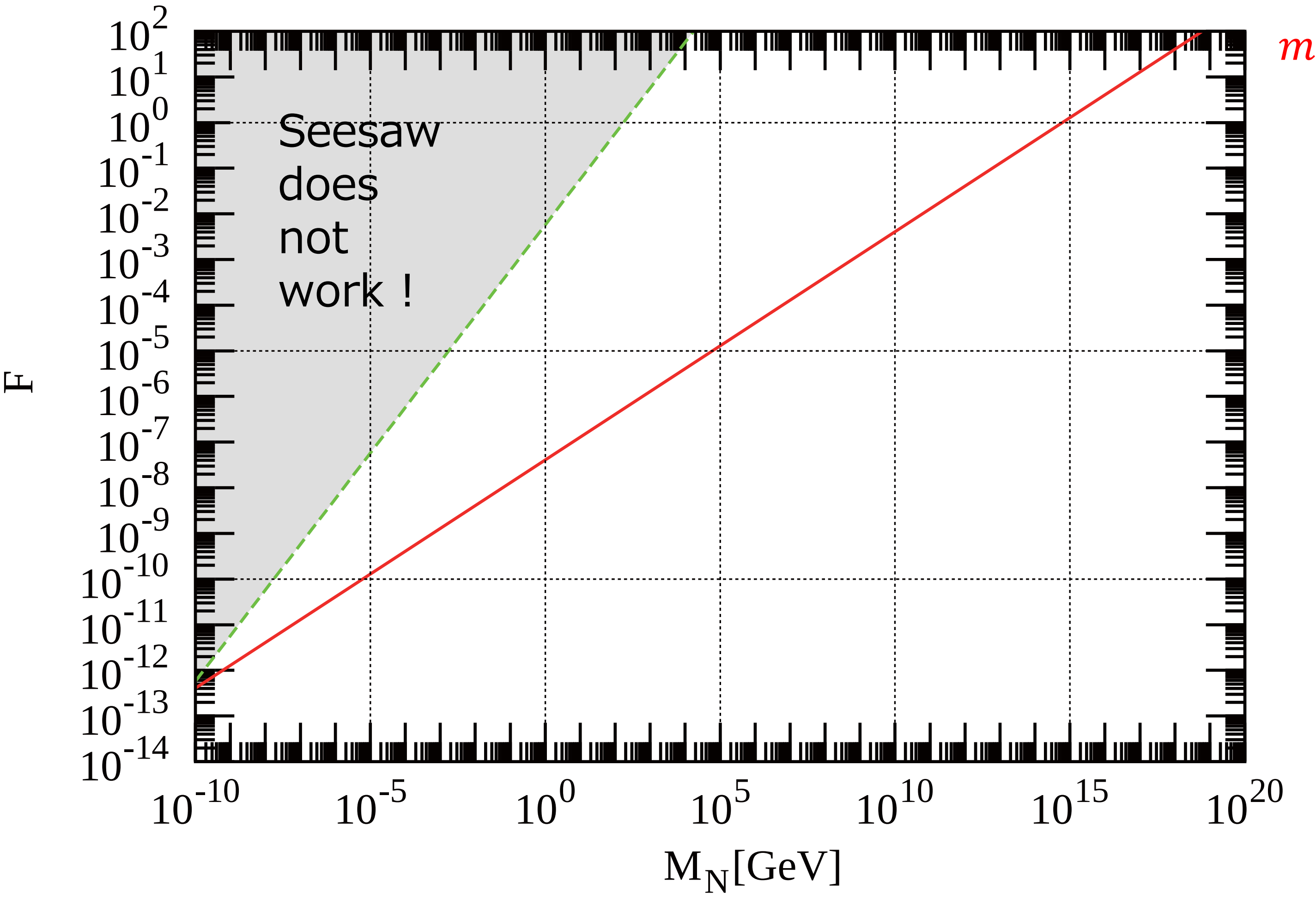
VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>45.0	95	ABREU	92B	DLPH	Dirac
>39.5	95	ABREU	92B	DLPH	Majorana
>44.1	95	ALEXANDER	91F	OPAL	Dirac
>37.2	95	ALEXANDER	91F	OPAL	Majorana
none 3–100	90	SATO	91	KAM2	Kamiokande II
>42.8	95	[1] ADEVA	90S	L3	Dirac
>34.8	95	[1] ADEVA	90S	L3	Majorana
>42.7	95	DECAMP	90F	ALEP	Dirac

[1] ADEVA 90S limits for the heavy neutrino apply if the mixing with the charged leptons satisfies $|U_{1j}|^2 + |U_{2j}|^2 + |U_{3j}|^2 > 6.2\times10^{-8}$ at $m_{L^0} = 20$ GeV and $> 5.1\times10^{-10}$

Yukawa Coupling and Mass of HNL

$$F = \frac{\sqrt{m_\nu M_N}}{\langle \Phi \rangle}$$

$m_\nu = 5 \times 10^{-11}$ GeV



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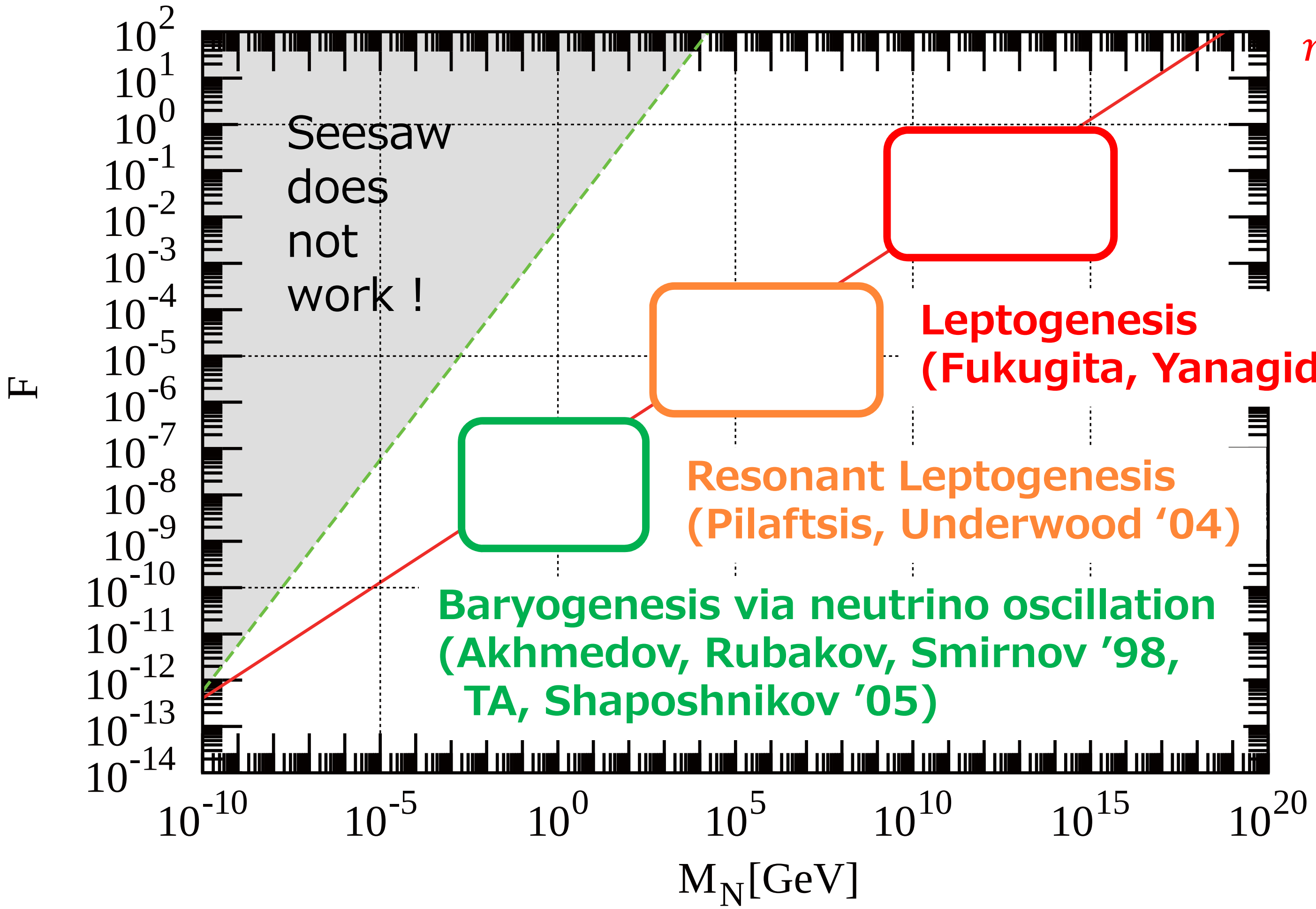


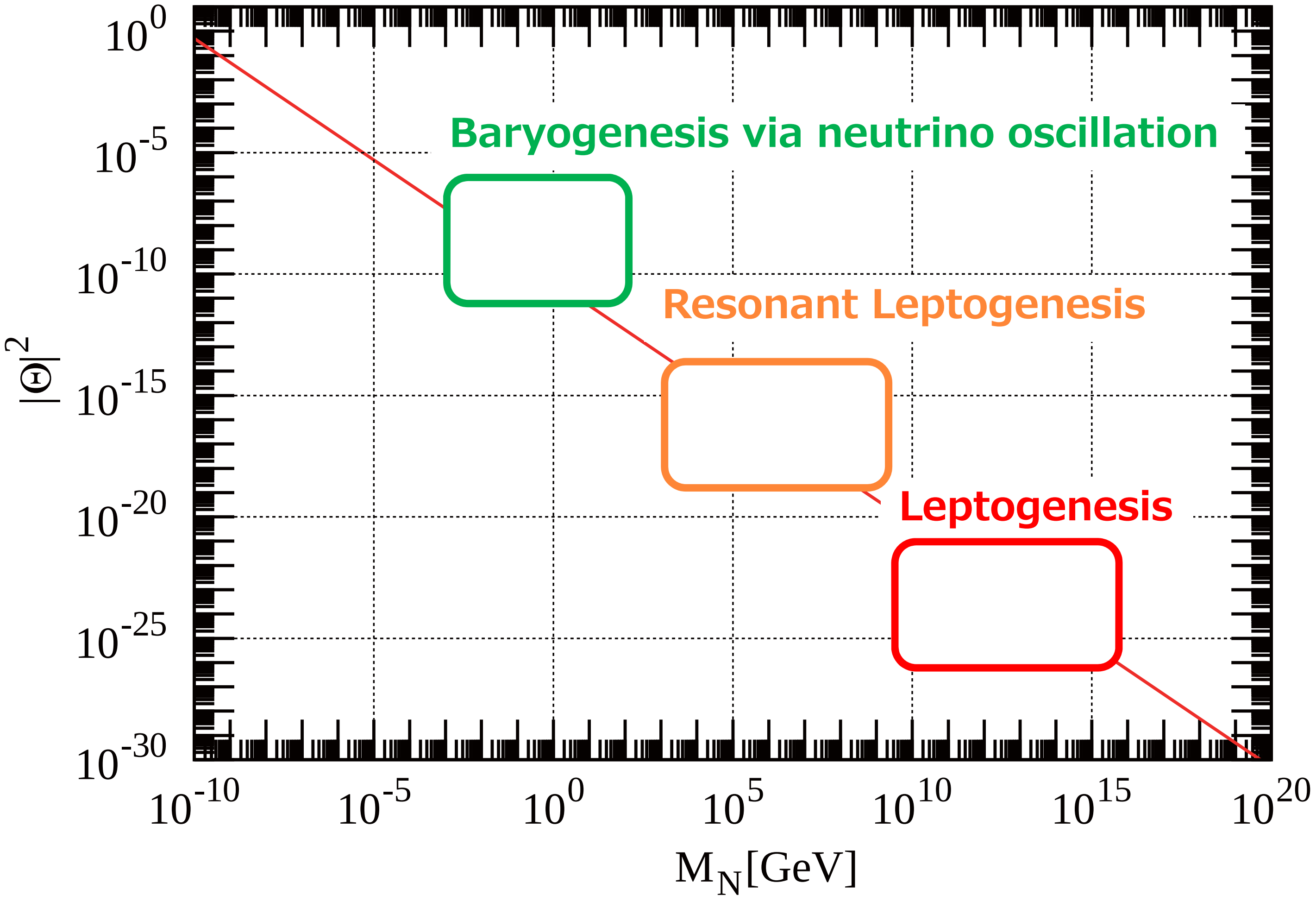
Leptogenesis
(Fukugita, Yanagida '86)

Resonant Leptogenesis
(Pilaftsis, Underwood '04)

Baryogenesis via neutrino oscillation
(Akhmedov, Rubakov, Smirnov '98,
TA, Shaposhnikov '05)

Mixing and Mass of HNL

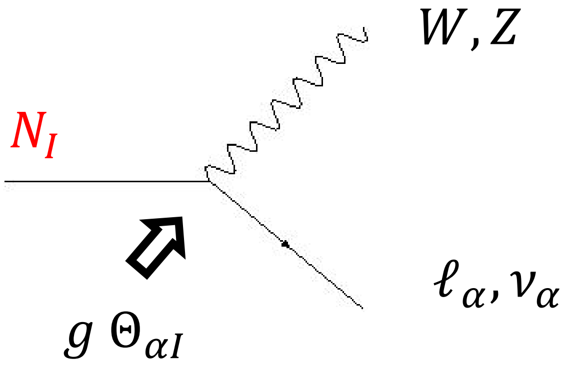
$$|\Theta|^2 = \frac{M_D^2}{M_N^2} = \frac{m_\nu}{M_N} \qquad m_\nu = 5 \times 10^{-11}\ \text{GeV}$$



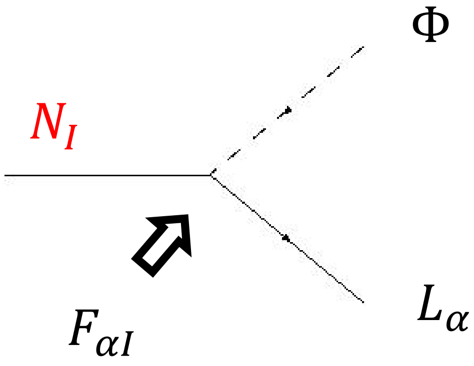
Important parameters of HNL

- Interactions of HNL

gauge interaction through mixing



Yukawa interaction



→ relevant for search experiments

- Two key parameters of HNL
  - mass M_I
  - mixing $\Theta_{\alpha I}$

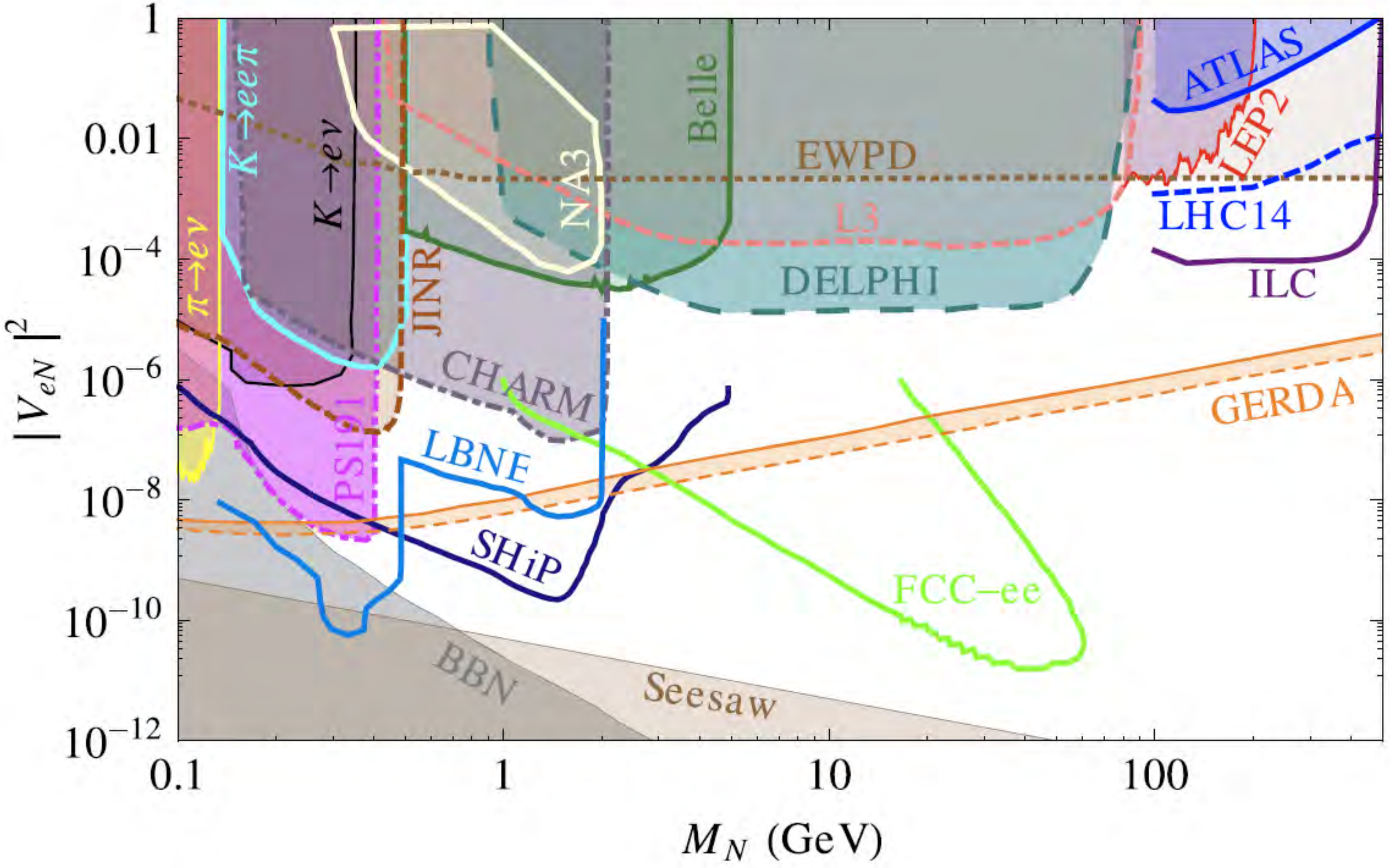
Limits on HNLs in the seesaw mechanism

See, for example, the recent analysis
Deppisch, DeV, Pilaftsis (arXiv:1502.06541)
and references therein.

Limits on mixing of HNL

- Limits on mixing Θ_{eI}

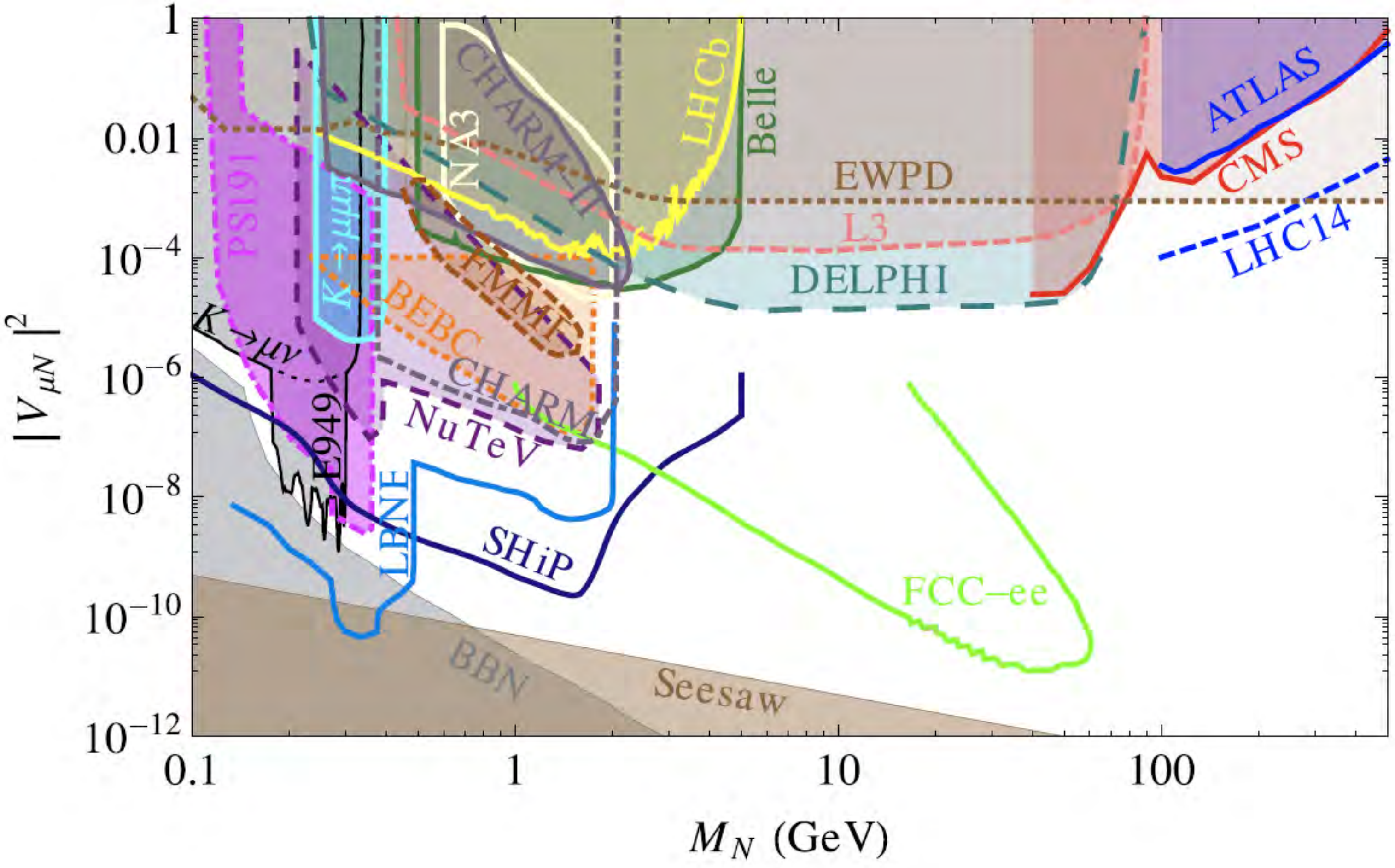
Deppisch, Dev, Pilaftis '15



Limits on mixing of HNL

- Limits on mixing $\Theta_{\mu I}$

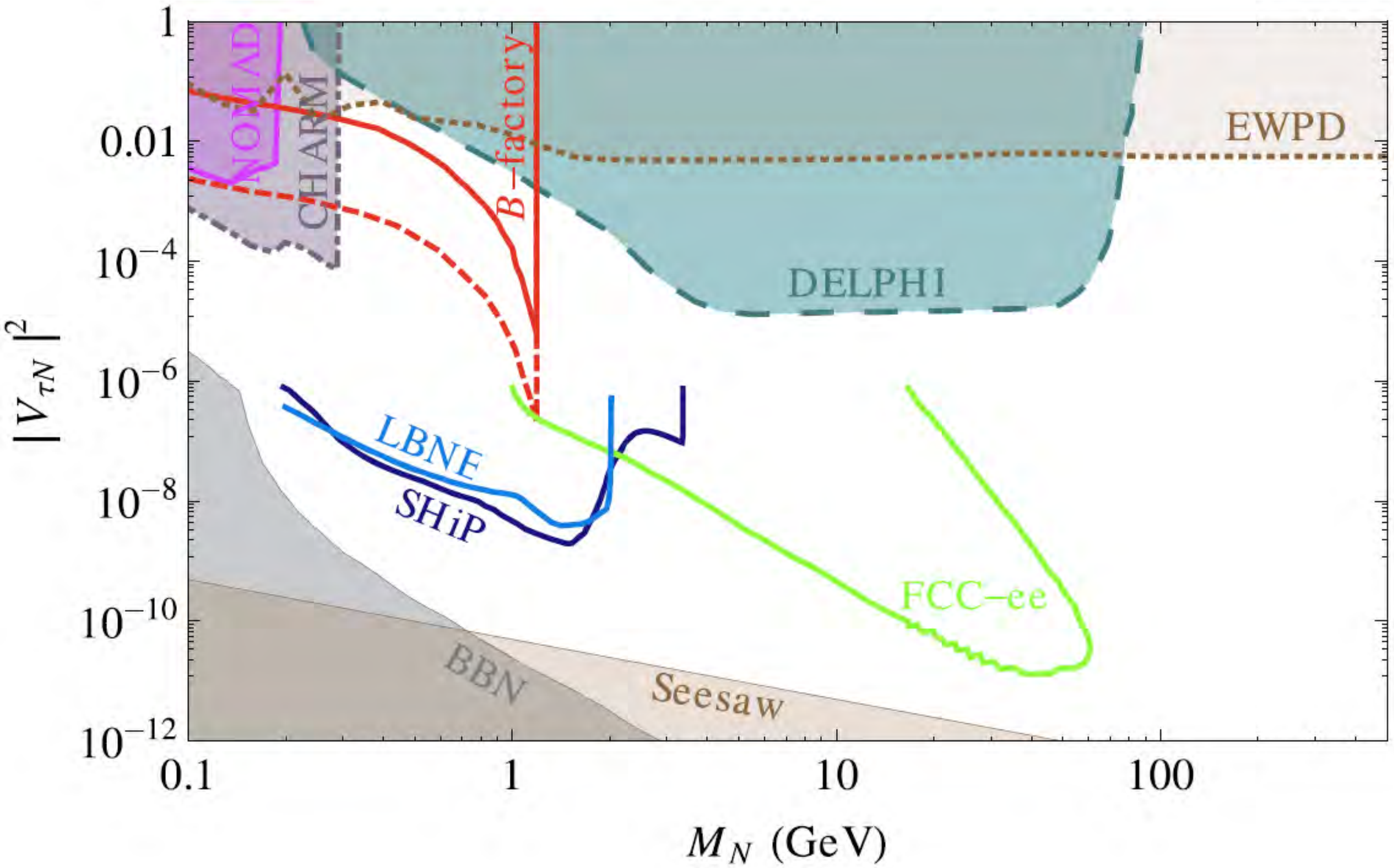
Deppisch, Dev, Pilaftis '15



Limits on mixing of HNL

- Limits on mixing $\Theta_{\tau I}$

Deppisch, Dev, Pilaftis '15



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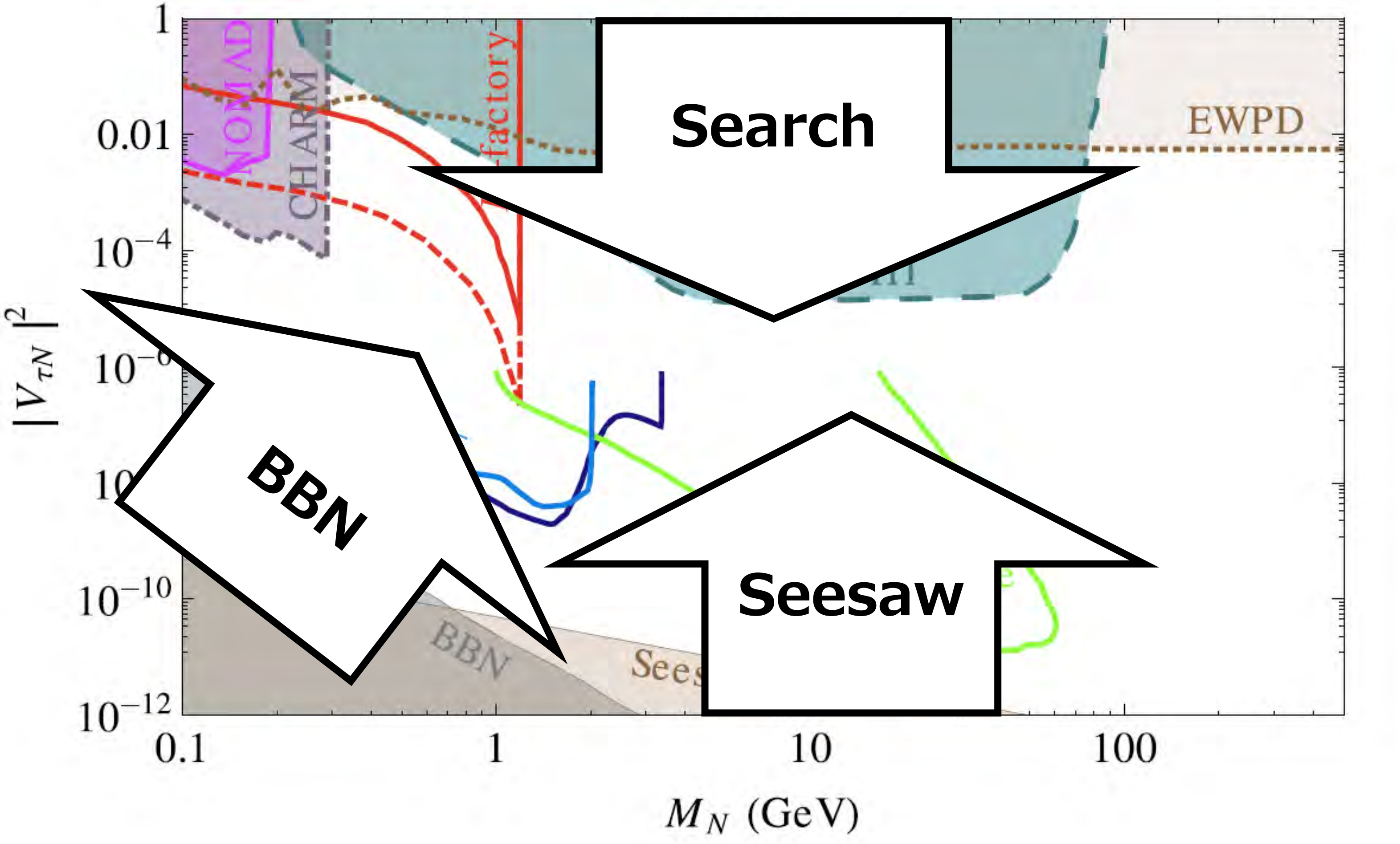


Bound from seesaw mechanism

- Mixings of HNL must be sufficiently large
  to explain masses of active neutrinos !

- Bound on the mixing of the lightest HNL N_1

TA, Tsuyuki '15

$$\boxed{|\Theta_1|^2 \geq \frac{m_l}{M_1}}$$

$$|\Theta_1|^2 \equiv \sum_{\alpha=e,\mu,\tau} |\Theta_{\alpha 1}|^2$$

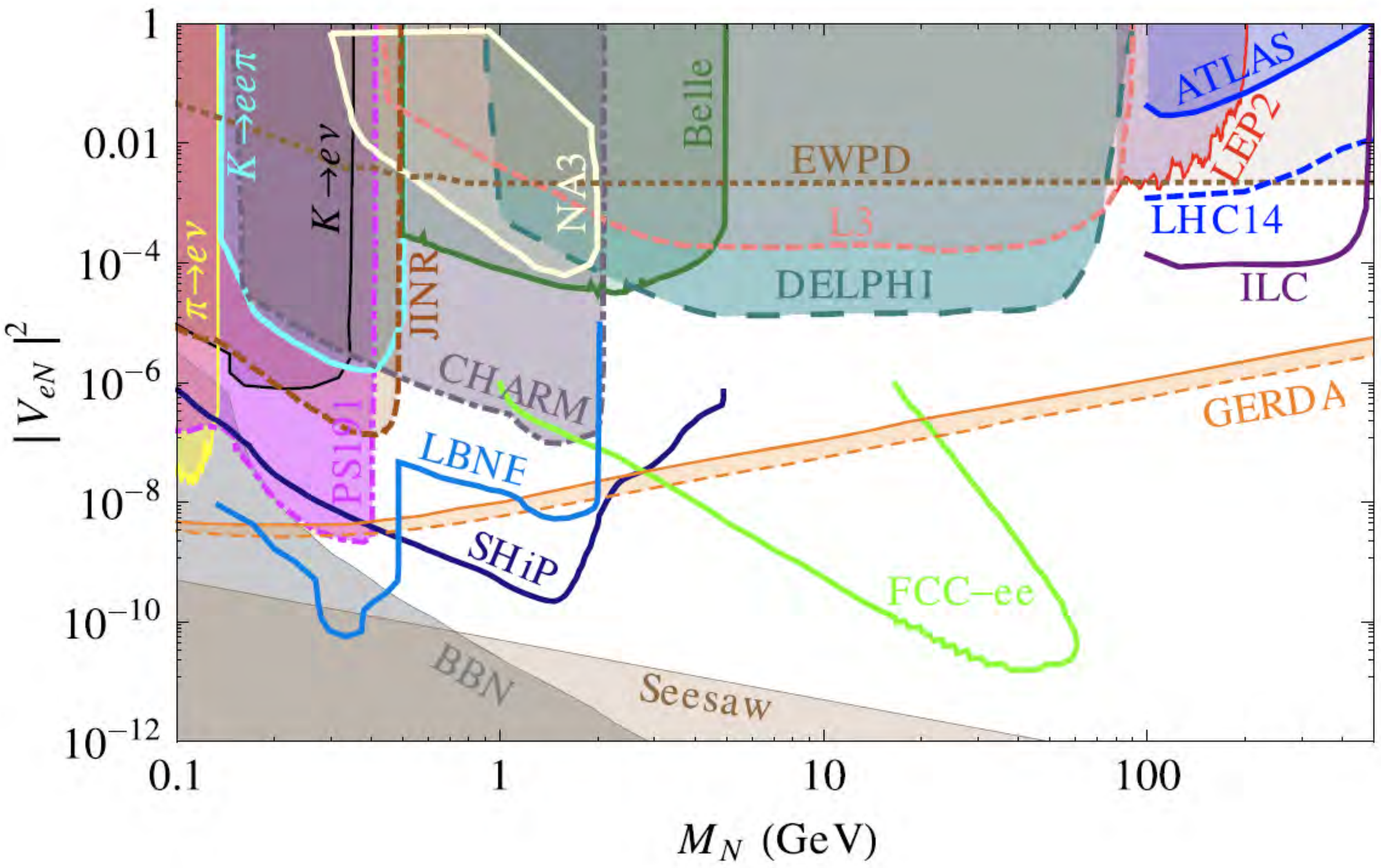
$$m_l = \begin{cases} m_1\ (m_3) \text{ in the NH (IH) for 3RHN } (\mathcal{N}=3) \\ m_2\ (m_1) \text{ in the NH (IH) for 2RHN } (\mathcal{N}=2) \end{cases}$$

NOTE: $|\Theta_1|^2$ can be zero for $\mathcal{N}=3$

Limits on mixing of HNL

- Limits on mixing Θ_{eI}

Deppisch, Dev, Pilaftis '15



Seesaw relation between mixings

- Neutrino mass matrix $\widehat{M_\nu} = \begin{pmatrix} \mathbf{0} & M_D \\ M_D^T & M_M \end{pmatrix}$ $\mathbf{0} = \left[\widehat{M_\nu}\right]_{\alpha\beta} = \left[\hat{U}\widehat{M_\nu}^{diag}\hat{U}^T\right]_{\alpha}$

Seesaw relation

$$0 = \sum_{i=1,2,3} m_i \, U_{\alpha i} U_{\beta i} + \sum_I M_I \, \Theta_{\alpha I} \, \Theta_{\beta I}$$

- When $|\Theta_1|^2 \gg m_\nu / M_1$,
  - Cancellation between HNLs is required ← fine tuning
  - Stability of this relation can be ensured by some symmetry

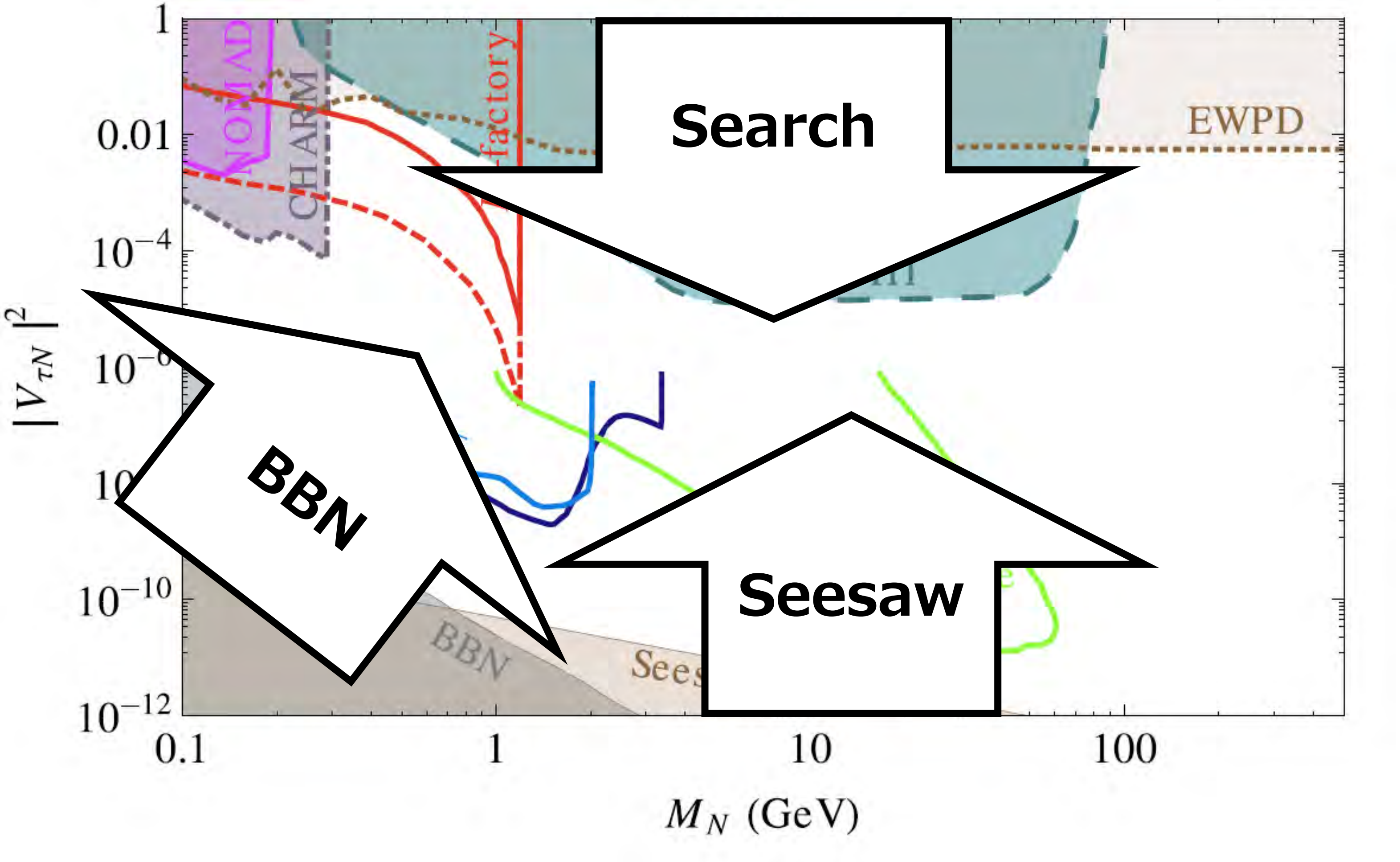
    Kersten, Sumirnov '07, ⋯

  - This relation is crucial in physics of right-handed neutrinos in the seesaw mechanism

Limits on mixing of HNL

- Limits on mixing $\Theta_{\tau I}$

Deppisch, Dev, Pilaftis '15



BBN constraint on lifetime

- Long-lived HNLs may spoil the success of BBN
  - Speed up the expansion of the universe
    - $\rho_{\mathrm{tot}} = \rho_{\mathrm{SM}} + \rho_N \quad \Rightarrow \quad H^2 = \frac{\rho_{\mathrm{tot}}}{3\,M_P^2}$
    - p-n conv. decouples earlier ⟹ overproduction of $^4\mathrm{He}$

      $n + \nu \leftrightarrow p + e^-, \ldots$
  - Distortion of spectrum of active neutrinos
    - $N \to \nu\,\bar{\nu}\,\nu,\ e^+\,e^-\,\nu, \ldots$
    - Additional neutrinos may not be thermalized

⇒ Upper bound on lifetime

⇒ Lower bound on mixing

Lifetime bound from BBN

Dolgov, Hansen, Raffelt, Semikoz '00

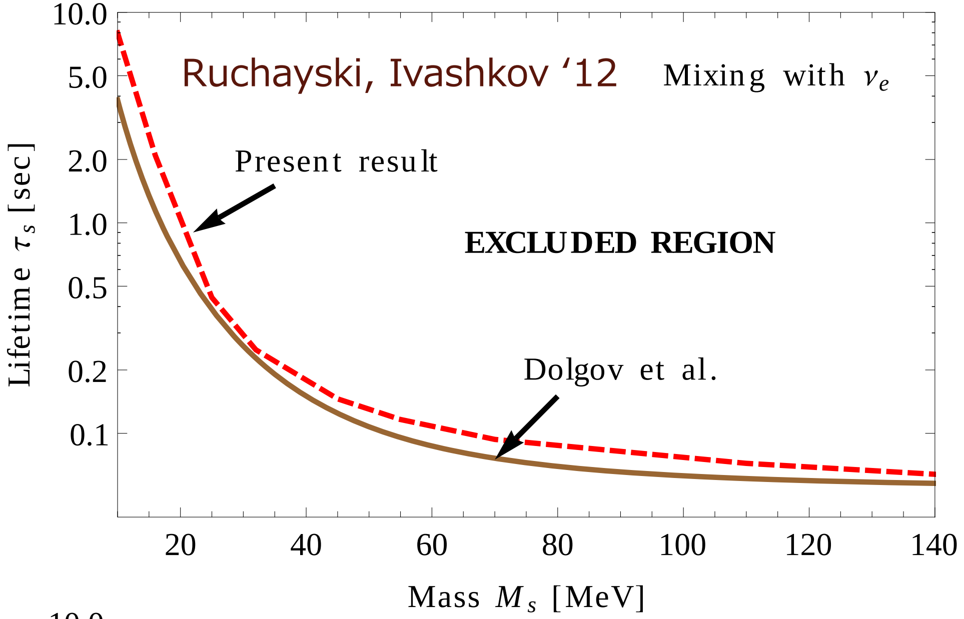
$M_N < m_\pi$

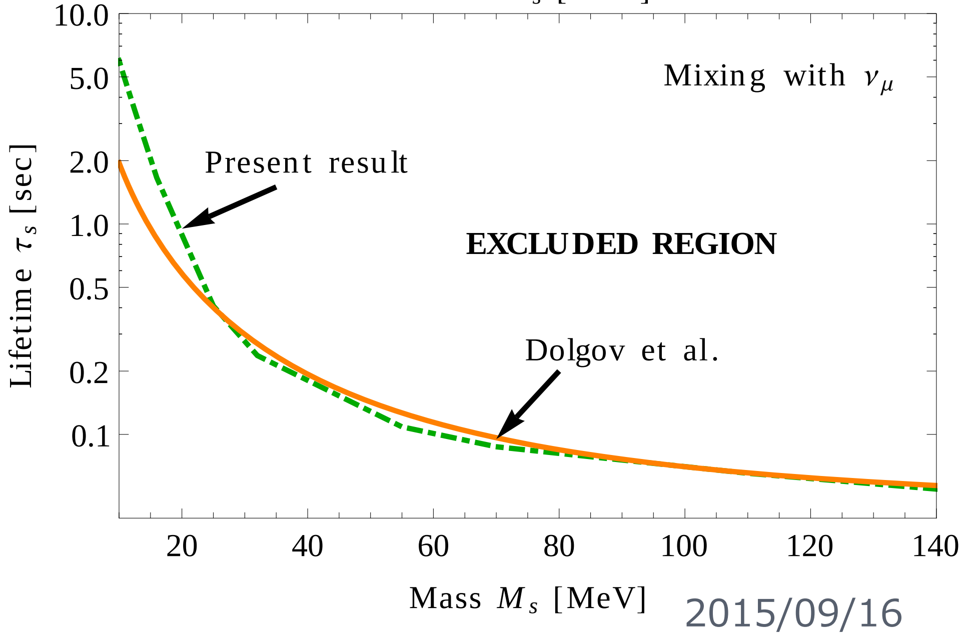
$$\boxed{\tau_N < t_1\,(M_N/\mathrm{MeV})^\beta + t_2}$$

	t_1(sec)	t_2(sec)	β
e	128.7	0.04179	-1.828
μ,τ	1699	0.0544	-2.652

$M_N > m_\pi$

$$\boxed{\tau_N < 0.1\ \mathrm{sec}}$$

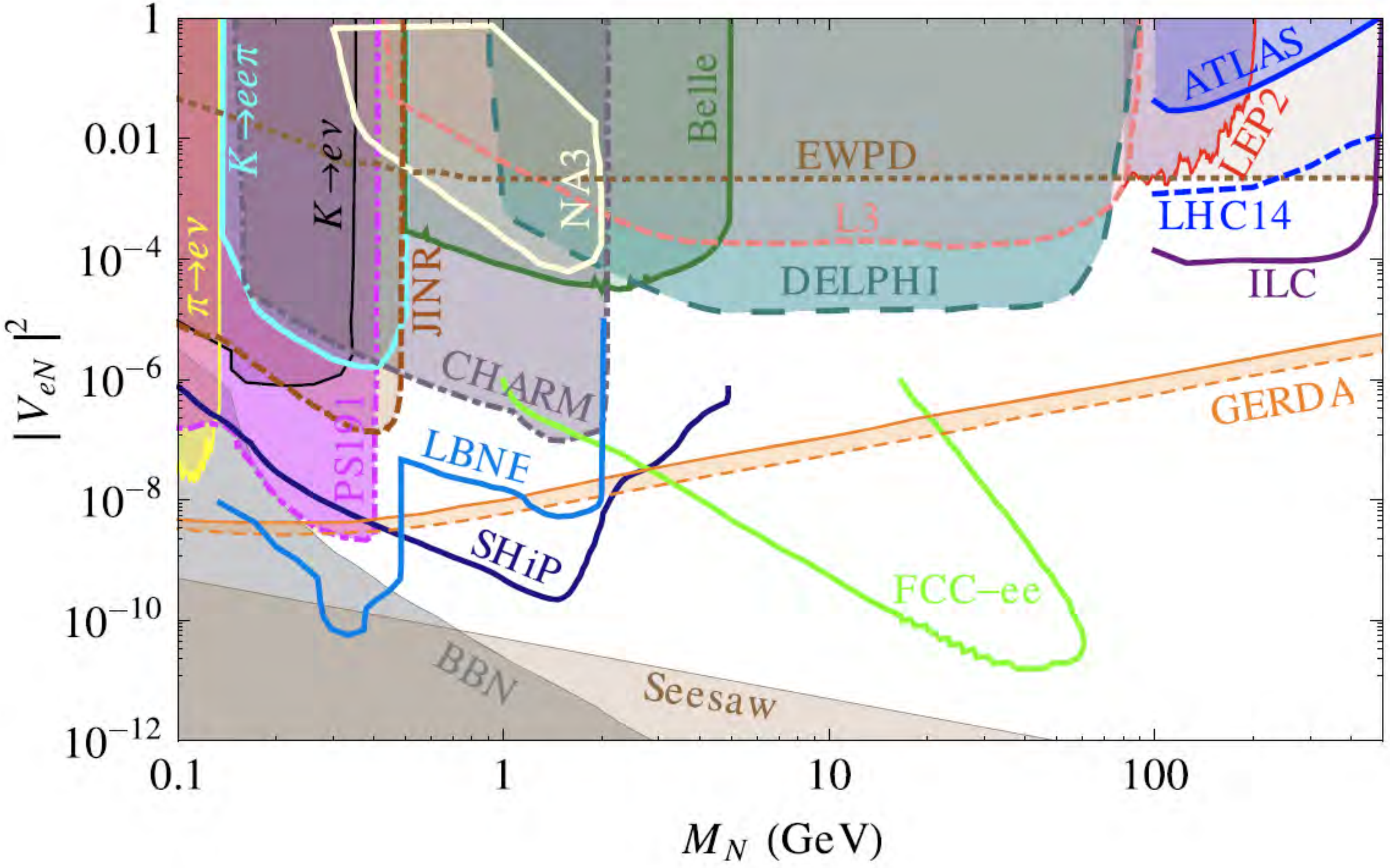




Limits on mixing of HNL

- Limits on mixing Θ_{eI}

Deppisch, Dev, Pilaftis ‘15



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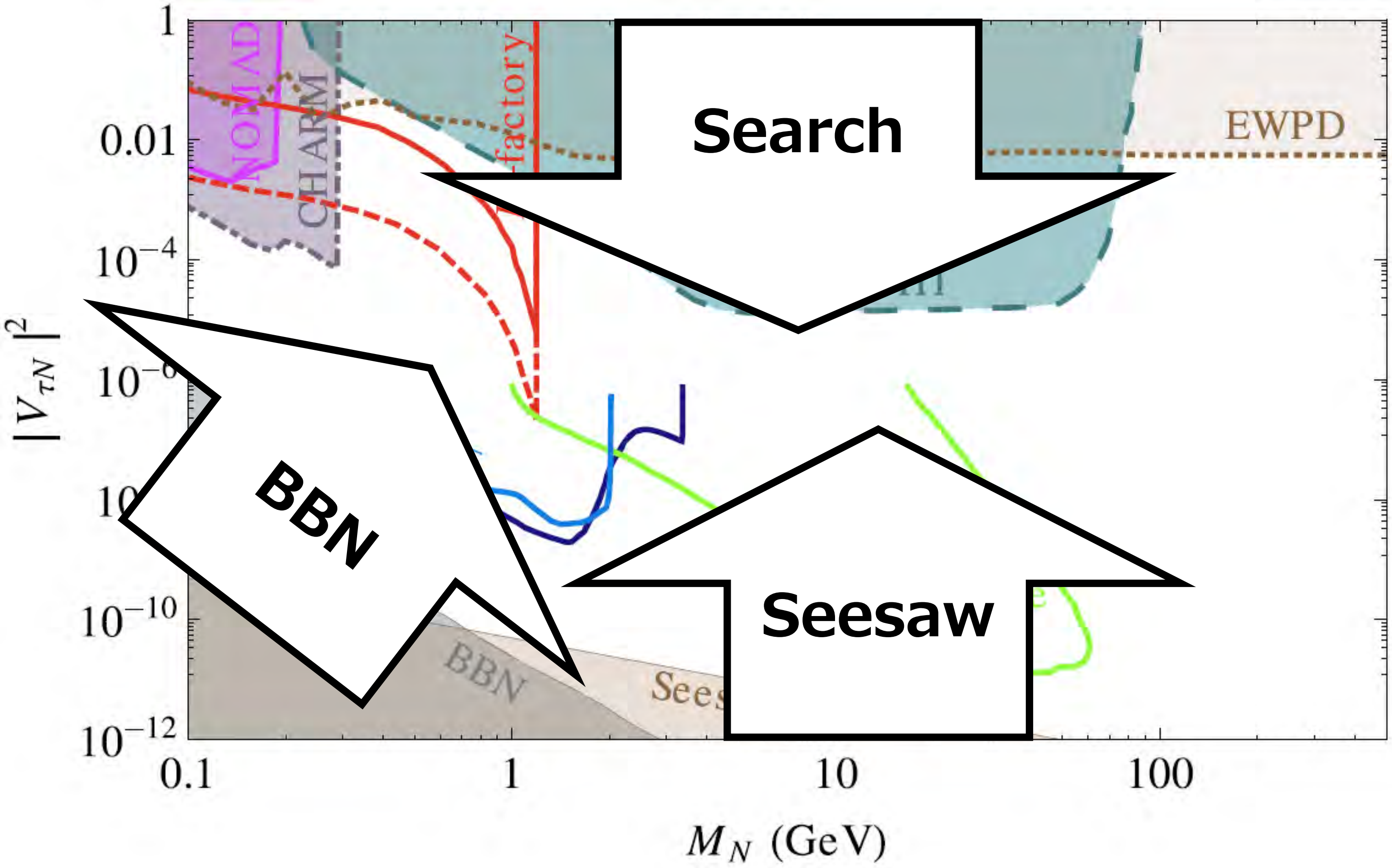
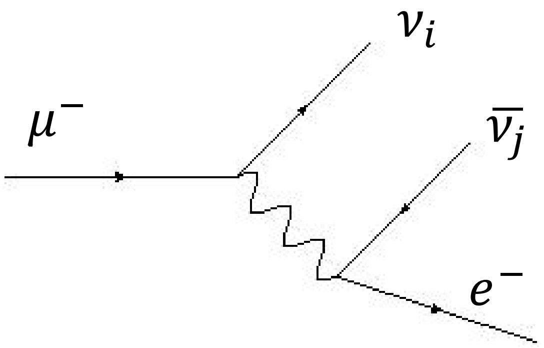


Indirect search (EWPD)

- PMNS mixing matrix U of active neutrinos is not "UNITARY"

$$\boxed{UU^\dagger + \Theta\Theta^\dagger = 1} \qquad \nu_{L\alpha} = U_{\alpha i}\,\nu_i + \Theta_{\alpha I}\,N_I^c$$

  - Impact of non-unitarity on μ decay: $\mu \to e\,\bar{\nu}_e\,\nu_\mu$



$$\Gamma = \Gamma^{SM} \times \left(UU^\dagger\right)_{ee} \times \left(UU^\dagger\right)_{\mu\mu}$$

$$G_F^{SM} = \sqrt{2}g^2/(8m_W^2)$$

$$\boxed{G_F\Big|_{OBS} = G_F^{SM} \times \left(UU^\dagger\right)_{ee} \times \left(UU^\dagger\right)_{\mu\mu}}$$

- Upper bound from EW precision data (EWPD) Antusch, Fischer '14

(s_W^2, $\Gamma(Z \to f\bar{f})$, Γ_{inv}, $\Gamma(W \to \ell\nu)$, m_W, lepton universality, CKM elements,)

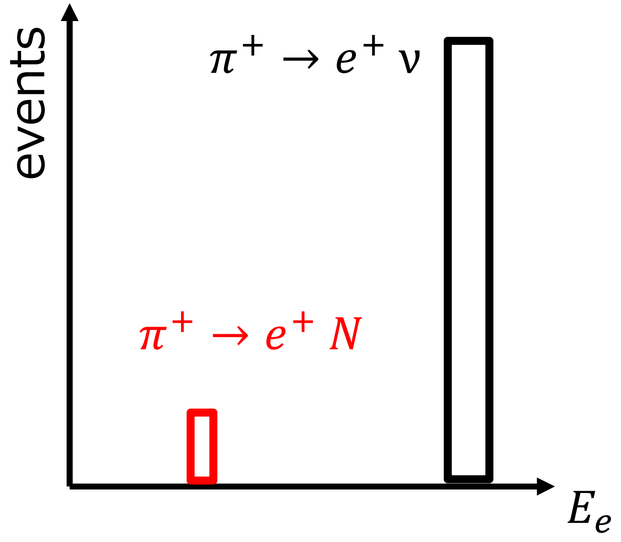
$$\boxed{|\Theta_e|^2 < 2.1 \times 10^{-3}\ ,\ |\Theta_\mu|^2 < 4 \times 10^{-4}\ ,\ |\Theta_\tau|^2 < 5.3 \times 10^{-3}}$$

@90% CL

Direct searches

- Peak search in meson decays ($M^+ \to \ell^+ N$) [Shrock '80]
  - Measure E_e in $\pi^+ \to e^+ N$

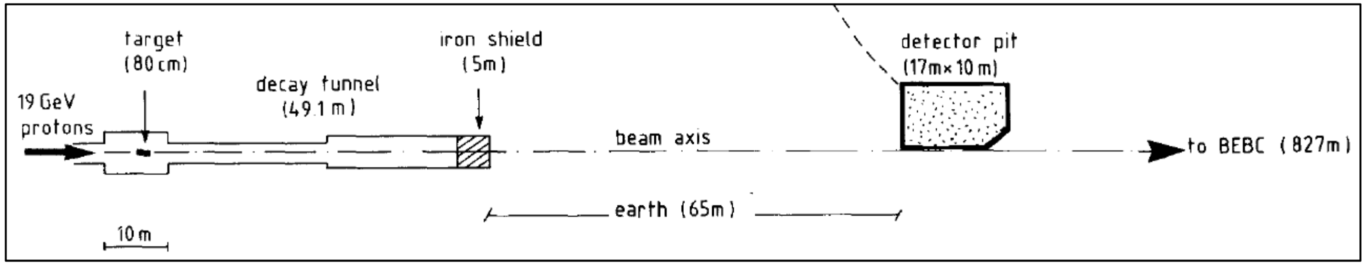
$$E_e = \frac{m_\pi^2 - m_e^2 - M_N^2}{2\, m_\pi}$$



- Beam dump experiments

$K^+ \to e^+ N$ $\quad$ $N \longrightarrow \ell^+ \ell^- \nu + c.c.$

CERN
PS191



→ SHiP, LBNE (now DUNE)

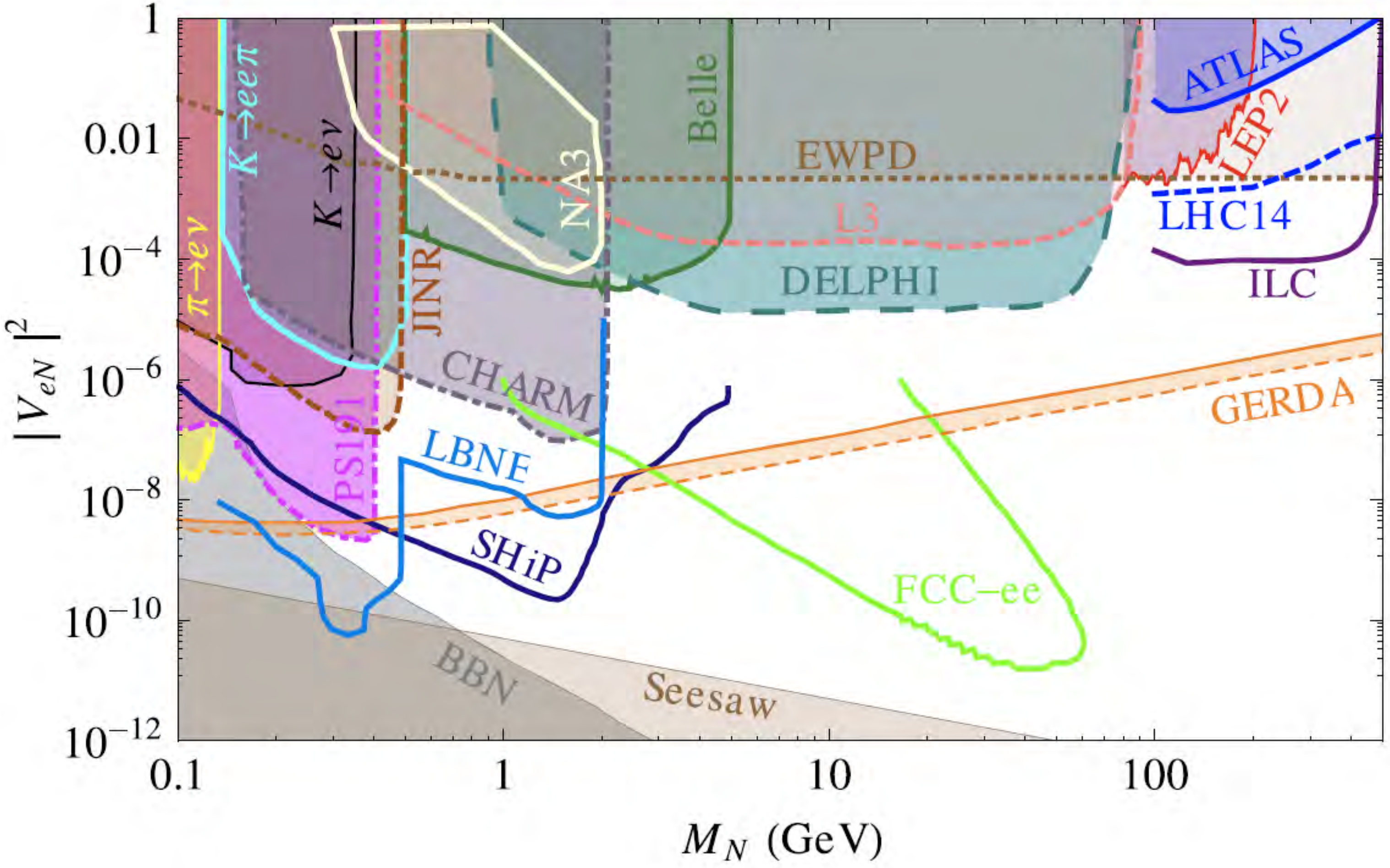
Direct searches

- Search @LEP
  - $Z \to \nu N \quad (3.3 \times 10^6\ Z)$
    → FCC-ee $(10^{12}\ Z)$
- Search @LEPII
  - $e^+e^- \to \nu N$ $(N \to e\, W$ with $W \to jets)$
    → ILC $(\sqrt{s} = 500\ \mathrm{GeV}, 500\ \mathrm{fb}^{-1})$
- Search @LHC
  - $pp \to \ell^+ N \to \ell^+\ \ell^+ j\, j$
- Search @LHCb
  - $B^- \to N\, \mu^- \to \pi^+\ \ \mu^-\ \mu^-$
- Search @Belle
  - $B^- \to X \ell N,\ N \to e^\pm \pi^\mp\ ,\ \mu^\pm \pi^\mp$

Limits on mixing of HNL

- Limits on mixing Θ_{eI}

Deppisch, Dev, Pilaftis ‘15



Lepton number violation in the seesaw mechanism

1) Neutrinoless double beta decay
2) Inverse neutrinoless double beta decay

Neutrinoless double beta ($0\nu\beta\beta$) decay

W.H. Furry 1939

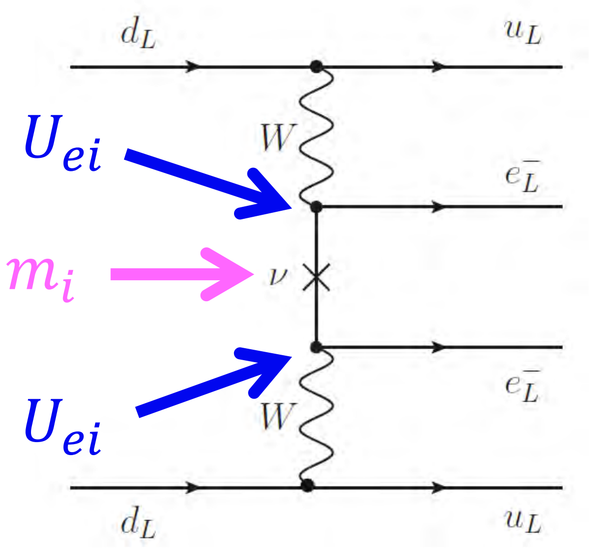
- Neutrinoless double beta ($0\nu\beta\beta$) decay

  $(Z, A) \rightarrow (Z+2, A) + 2e^-$

  - LNV ($\Delta L = +2$) process mediated by Majorana massive neutrinos
  - Half-life of $0\nu\beta\beta$ decay

$$T_{1/2}^{-1} = A \frac{m_p^2}{\langle p^2 \rangle^2} |m_{\text{eff}}|^2$$

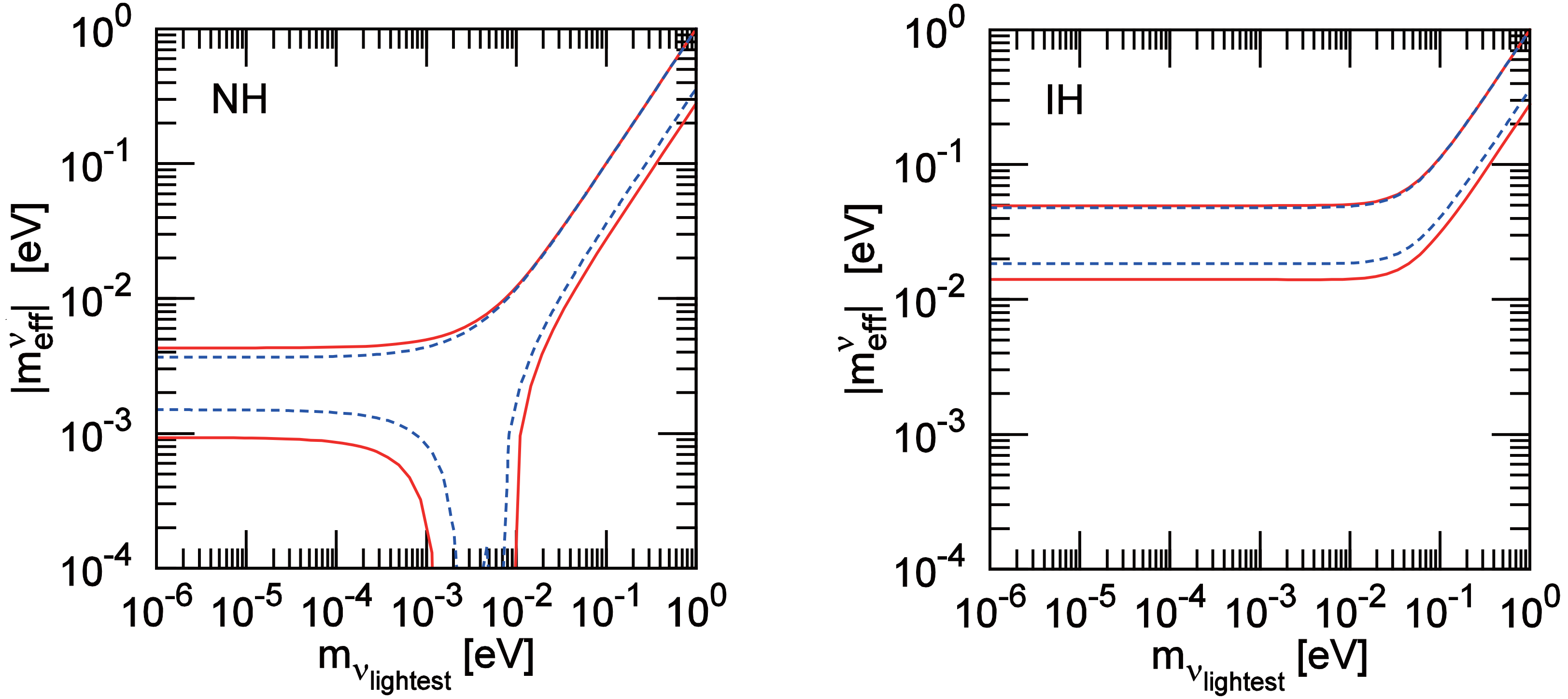
$$\boxed{m_{\text{eff}} = \sum_{i=1,2,3} m_i \, U_{ei}^2 + \; \ldots}$$



Faessler, Gonzalez, Kovalenko, Simkovic '14

$0\nu\beta\beta$ decay

- Contribution from active neutrinos $m^{\nu}_{\rm eff} = \sum_{i=1,2,3} m_i\, U_{ei}^2$



Planck 2015

$\Sigma\, m_i < 0.23$ eV

$m_{\nu\rm lighest} < 0.07\ (0.06)$ eV

$m_{\rm eff} \lesssim (0.185 - 0.276)$ eV

KamLAND-Zen 1211.3863 ^{136}Xe

$m_{\rm eff} \lesssim (0.213 - 0.308)$ eV

GERDA 1307.4720 ^{76}Ge

$0\nu\beta\beta$ decay in the seesaw

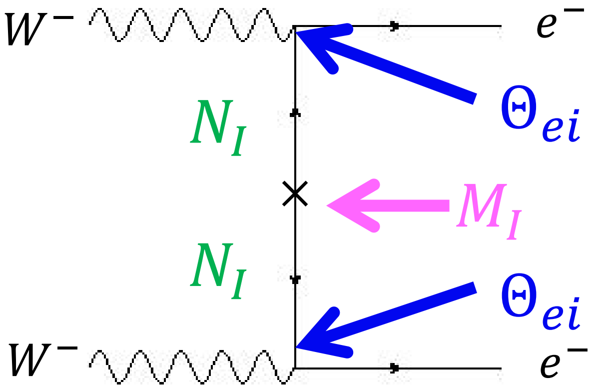
$$m_{\text{eff}} = \sum_{i=1,2,3} m_i\, U_{ei}^2 + \sum_I f_\beta(M_I)\, M_I\ \Theta_{eI}^2$$

active neutrinos

heavy neutral leptons

- HNLs may give a significant contribution to m_{eff} !

$$m_{eff}^N = \begin{cases} M_I\, \Theta_{eI}^2 & (M_I^2 \ll \langle p\rangle^2) \\ \dfrac{\langle p\rangle^2}{M_I}\Theta_{eI}^2 & (M_I^2 \gg \langle p\rangle^2) \end{cases}$$



$$f_\beta(M_I) = \frac{\langle p\rangle^2}{\langle p\rangle^2 + M_I^2}$$

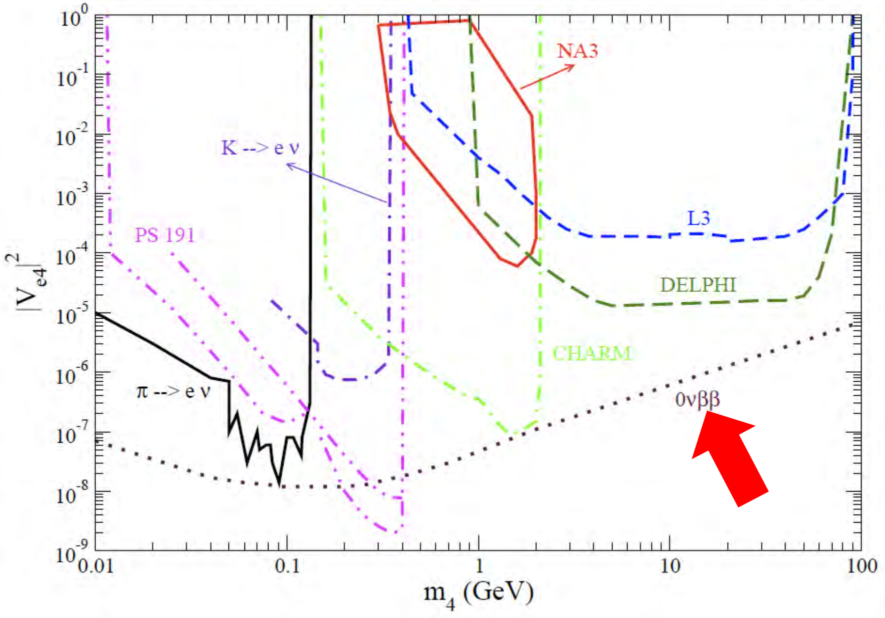
$$\sqrt{\langle p^2\rangle} \sim 200 \text{ MeV}$$

Faessler, Gonzalez, Kovalenko, Simkovic '14

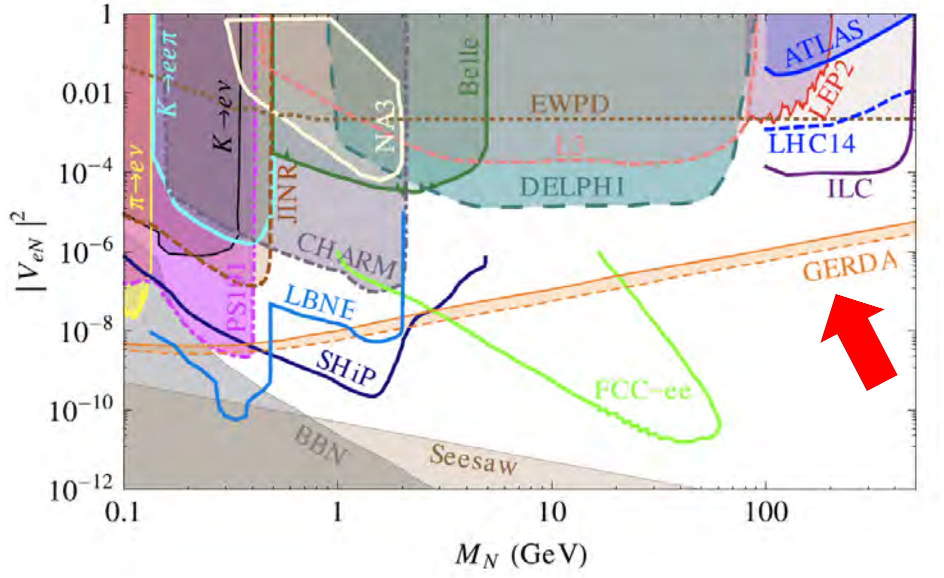
$0\nu\beta\beta$ decay in the seesaw

- Stringent constraint on the mixing:

Atre, Han, Pascoli, Zhang '09



Deppisch, Dev, Pilaftsis '15



This bound cannot be applied to
some cases in the seesaw mechanism !

$0\nu\beta\beta$ decay in the seesaw

- Seesaw relation plays an important role !

$$\boxed{0=\sum_i m_i U_{ei}^2+\sum_I M_I\,\Theta_{eI}^2}$$

- When all HNLs are light $M_I \ll \sqrt{\langle p^2\rangle}\sim 0.1$ GeV (i.e. $f_\beta=1$),

$$m_{\mathrm{eff}}=\sum_i m_i U_{ei}^2+\sum_I f_\beta(M_I)M_I\,\Theta_{eI}^2=0$$

  - This shows $0\nu\beta\beta$ decay does not occur even if neutrinos are Majorana fermions.
  - In this case, there is no bound on the mixing from $0\nu\beta\beta$ decay

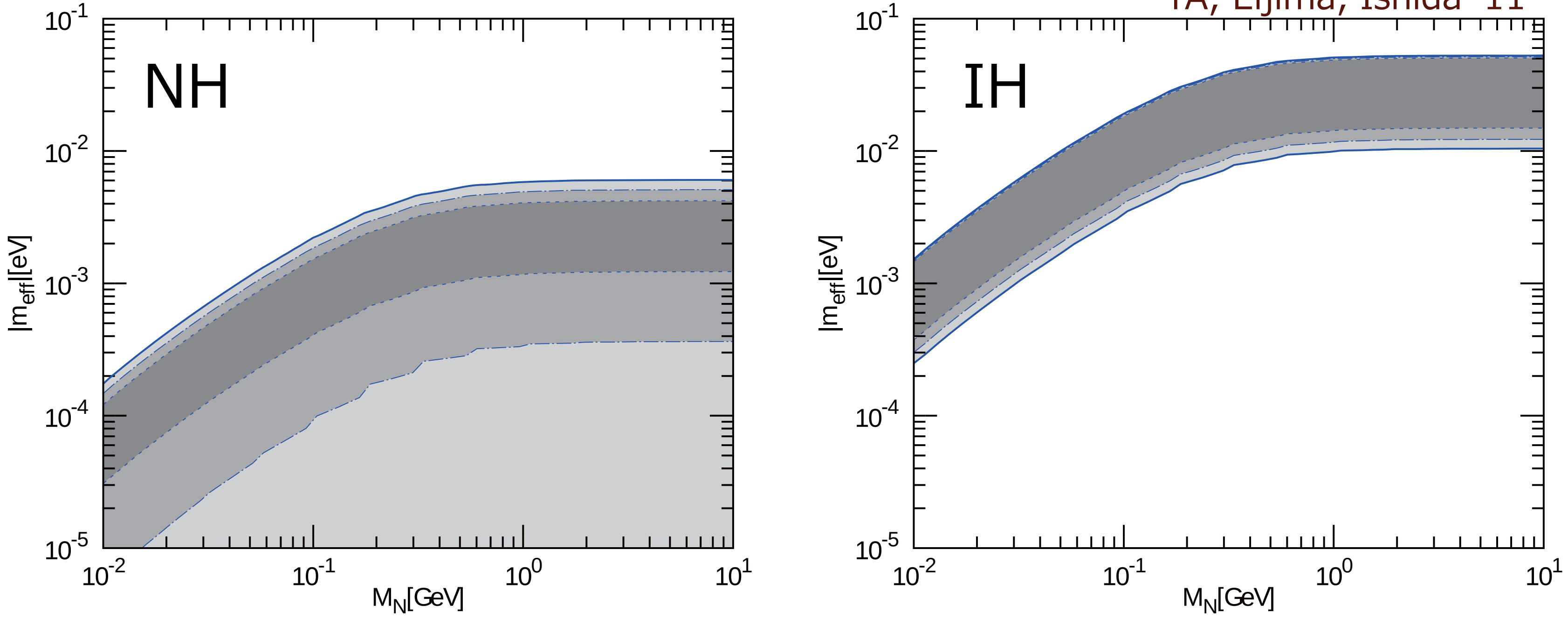
$0\nu\beta\beta$ decay in the seesaw

- When all HNLs are degenerate $M_I = M_N$,

$$m_{\rm eff} = \sum_i m_i U_{ei}^2 + \sum_I f_\beta(M_I) M_I\, \Theta_{eI}^2 = {\rm m}_{\rm eff}^{\nu}[\,1\, - f_\beta(M_N)]$$

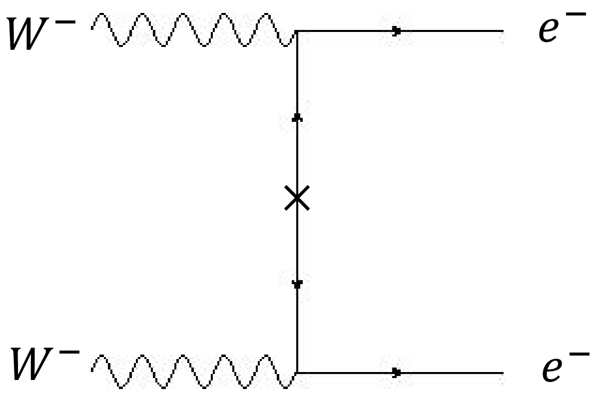
  - This shows $0\nu\beta\beta$ decay does not depend on the mixing of HNL
  - In this case, there is no bound on the mixing from $0\nu\beta\beta$ decay

TA, Eijima, Ishida '11

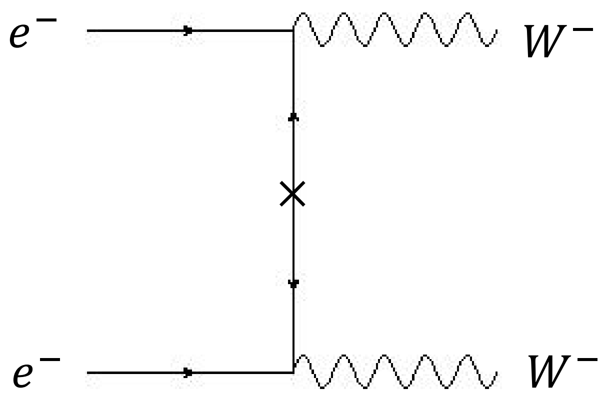


Another example of LNV:

$$e^- e^- \rightarrow W^- W^-$$



$0\nu\beta\beta$ decay

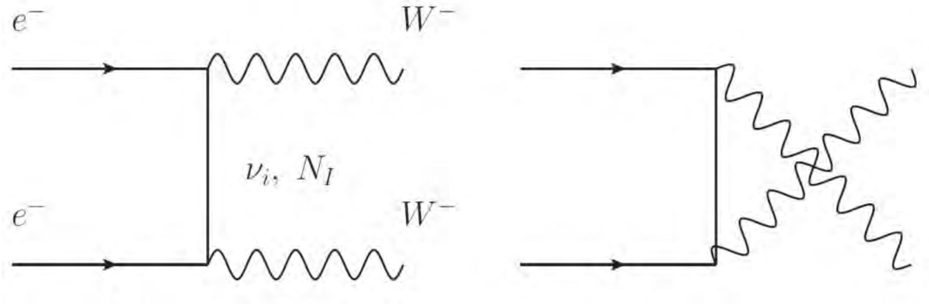


Inverse $0\nu\beta\beta$ decay

Inverse neutrinoless double beta ($i0\nu\beta\beta$) decay

[T. G. Rizzo 1982]

- $e^-e^- \to W^-W^-$ offers test for LNV



- e^-e^- collision is option of ILC, CLIC
- Advantages over $0\nu\beta\beta$ decay
  - Signal is clean
  - Free from uncertainty in nuclear matrix elements
  - Can occur even if $0\nu\beta\beta$ decay is absent

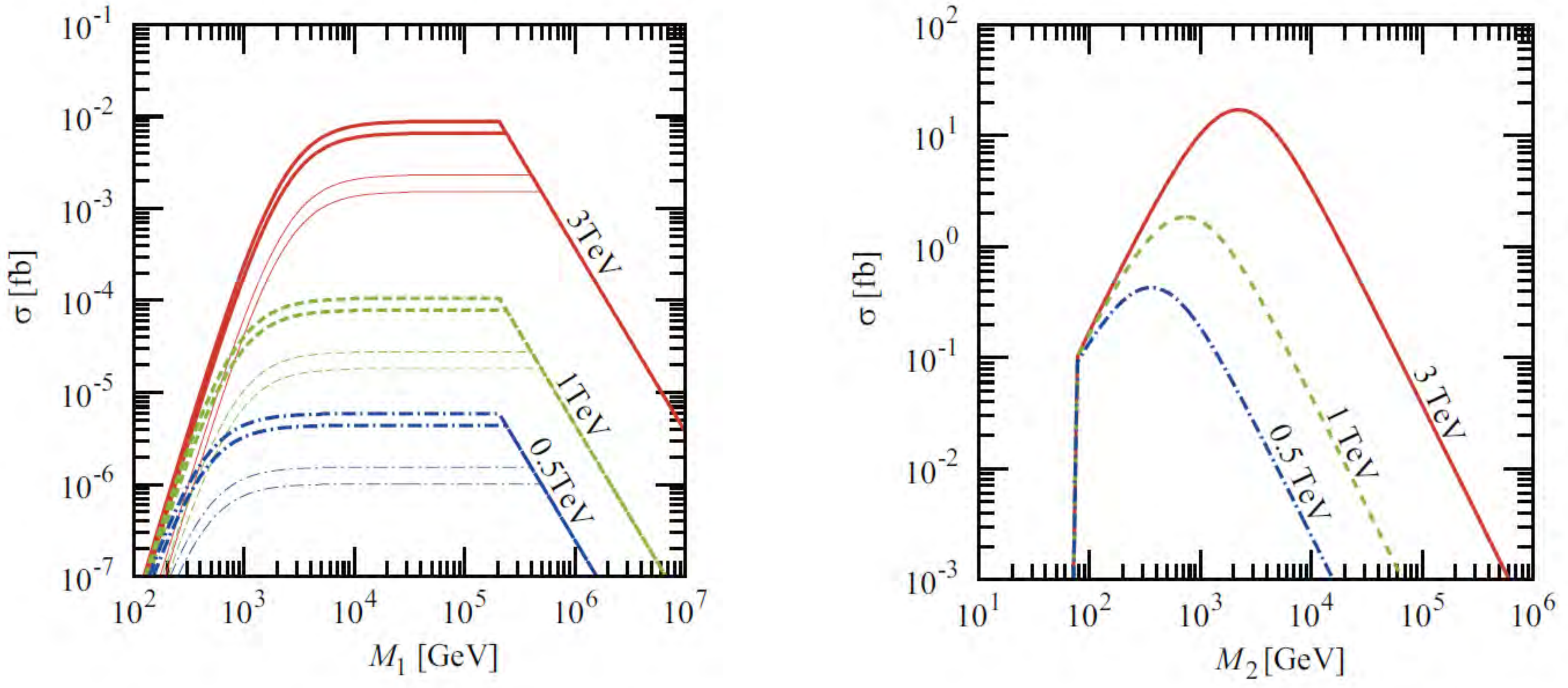
→ Inverse $0\nu\beta\beta$ decay and $0\nu\beta\beta$ decay are complementary tests for LNV in the seesaw mechanism

Inverse $0\nu\beta\beta$ decay in the seesaw

- Maximal cross section of $e^- e^- \to W^- W^-$

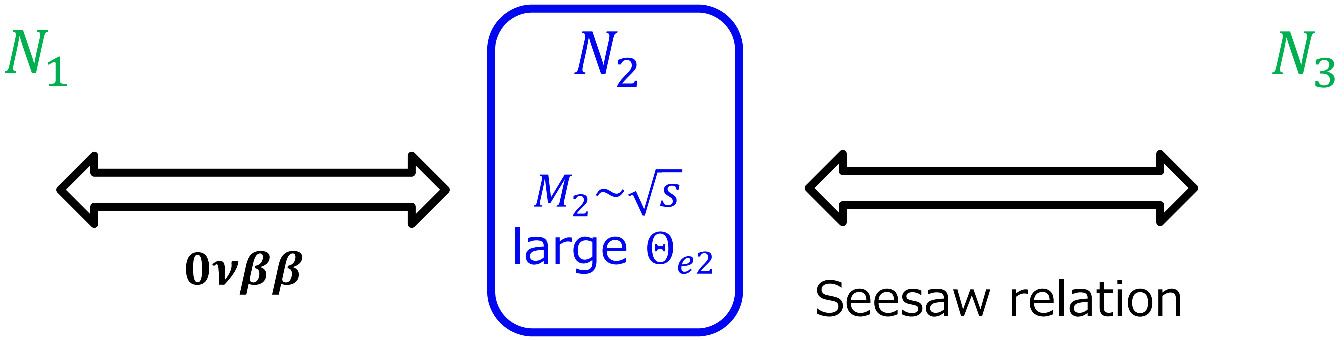
TA, Tsuyuki '15

$\mathcal{N}=2$ $\mathcal{N}=3$



Inverse $0\nu\beta\beta$ decay in the seesaw

- How obtain large cross section ?   --- idea



N_1

N_2

$M_2 \sim \sqrt{s}$
large Θ_{e2}

N_3

$0\nu\beta\beta$

Seesaw relation

$$0 \simeq \Theta_{e1}^2 \frac{\langle p^2 \rangle}{M_1} + \Theta_{e2}^2 \frac{\langle p^2 \rangle}{M_2}$$

$$0 \simeq \Theta_{e2}^2 M_2 + \Theta_{e3}^2 M_3$$

\# of right-handed neutrinos ≥ 3

- Even with the seesaw relation and the $0\nu\beta\beta$ bound, the mixing of N_2 can be large as

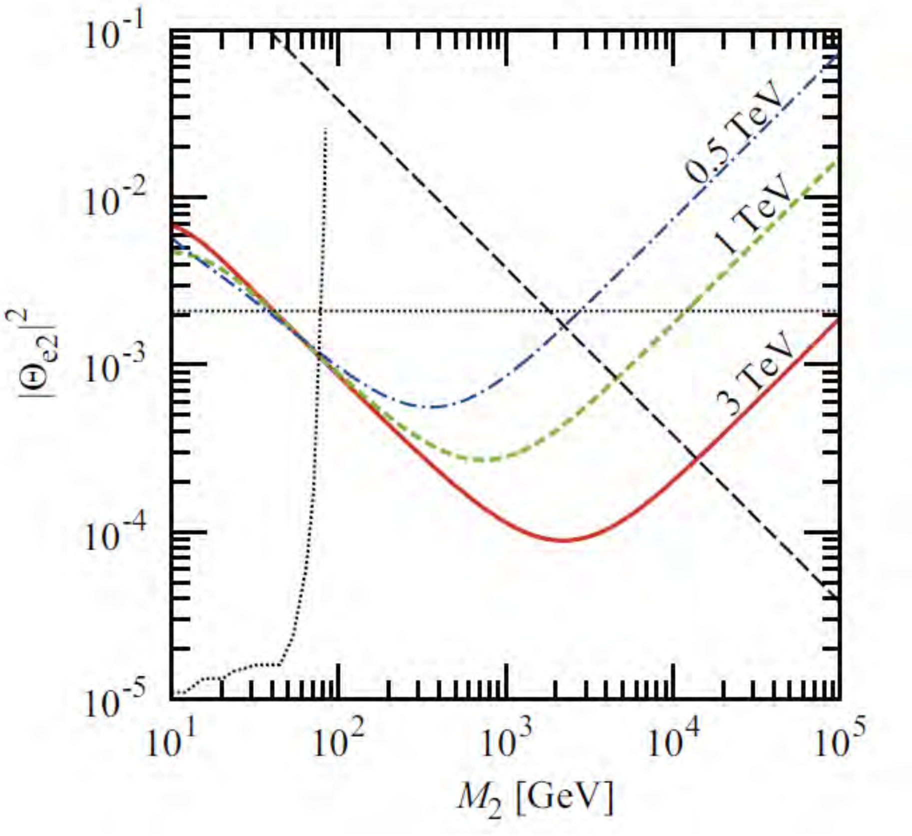
$$|\Theta_{e2}|^2 < |\Theta_e|^2_{EWPD} = 2.1 \times 10^{-3}$$

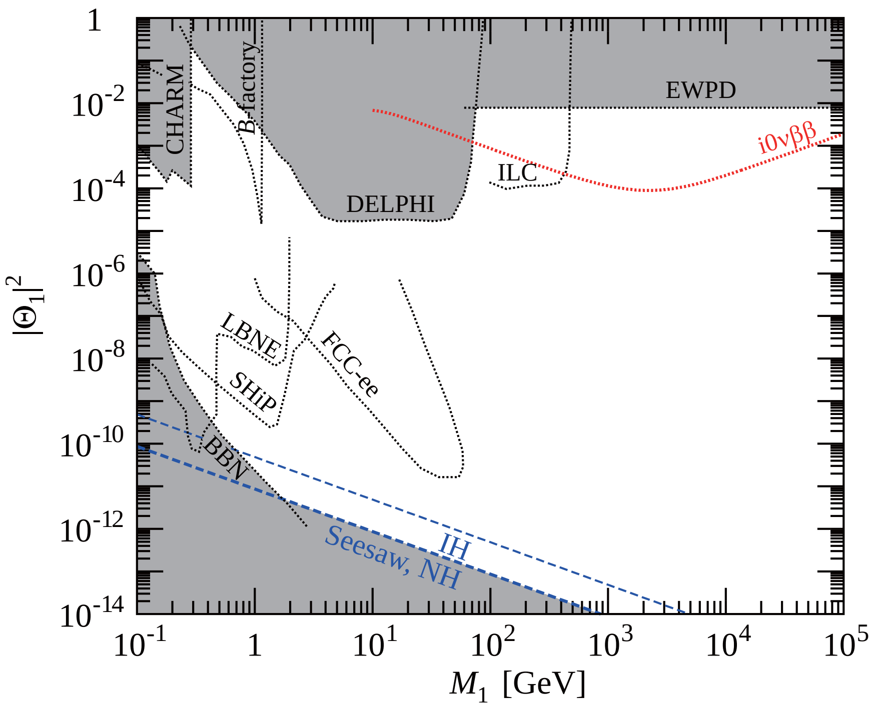
→ Large $\sigma(e^- e^- \to W^- W^-)$

Inverse $0\nu\beta\beta$ decay in the seesaw

- Sensitivity of mixing (@$100\ \mathrm{fb}^{-1}$)

TA, Tsuyuki '15





LNV in the seesaw

- Comments on inverse $0\nu\beta\beta$ decay
  - Polarized beams
    - cross section becomes four times larger
    - turned on/off by flipping beam polarization
  - To avoid the $0\nu\beta\beta$ bound,
    HNL with $M_1 < M_2$ and $\Theta_{e1} = -\frac{M_1}{M_2}\Theta_{e2}$ is required
    - good target for experimental searches
  - Inverse $0\nu\beta\beta$ is severely restricted from perturbativity

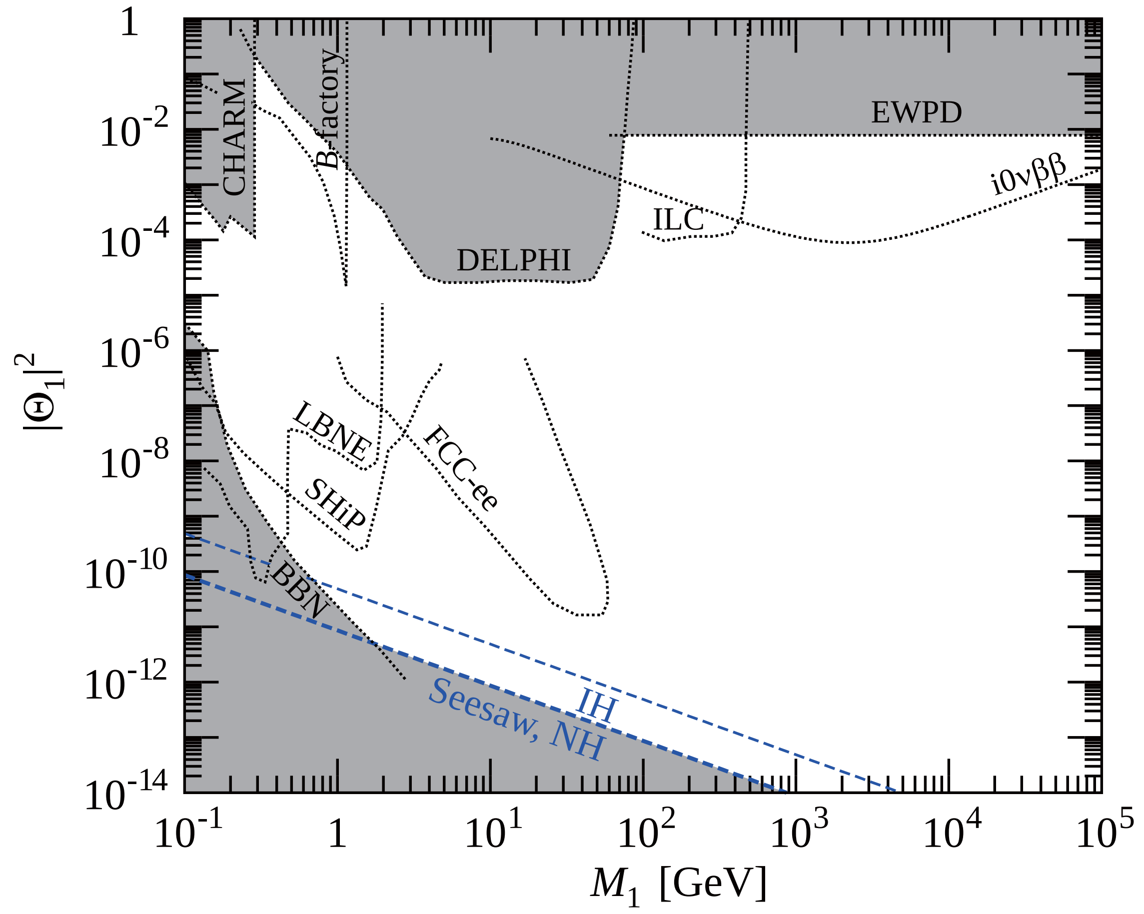
- Other LNV processes in the seesaw mechanism
  - $pp \to \ell^+ N \to \ell^+ \ell^+ j\, j$ @LHC
  - $B^+ \to \ell^+ N \to \ell^+ \ell^+ \pi^-$ @SuperKEKB
  - $K^+ \to \ell^+ N \to \ell^+ \ell^+ \pi^-$ @J-PARC
  - $\cdots$

Perturbativity in the seesaw mechanism

TA, Tsuyuki arXiv:1509.02678

Testability of HNL

- HNL N_1 can be observed if it has sufficiently small mass and large mixing $|\Theta_1|^2 \gg m_\nu / M_1$



What is implication of N_1 with large mixing?

Implication of N_1 with large mixing

- Seesaw relation:

$\mathcal{N}$: # of RHNs

$$0 = \cancel{\sum_i U^2_{\alpha i}\, m_i} + \Theta^2_{\alpha 1}\, M_1 + \sum_{I=2}^{\mathcal{N}} \Theta^2_{\alpha I}\, M_I$$

- There exists at least one HNL N_2 to cancel the N_1 contribution !

$$\Theta^2_{\alpha 2} M_2 = -\Theta^2_{\alpha 1} M_1$$

  - Mixings: $|\Theta_{\alpha 2}|^2 = \dfrac{M_1}{M_2} |\Theta_{\alpha 1}|^2$
  - Yukawa couplings: $|F_{\alpha 2}|^2 = \dfrac{M_2}{M_1} |F_{\alpha 1}|^2$

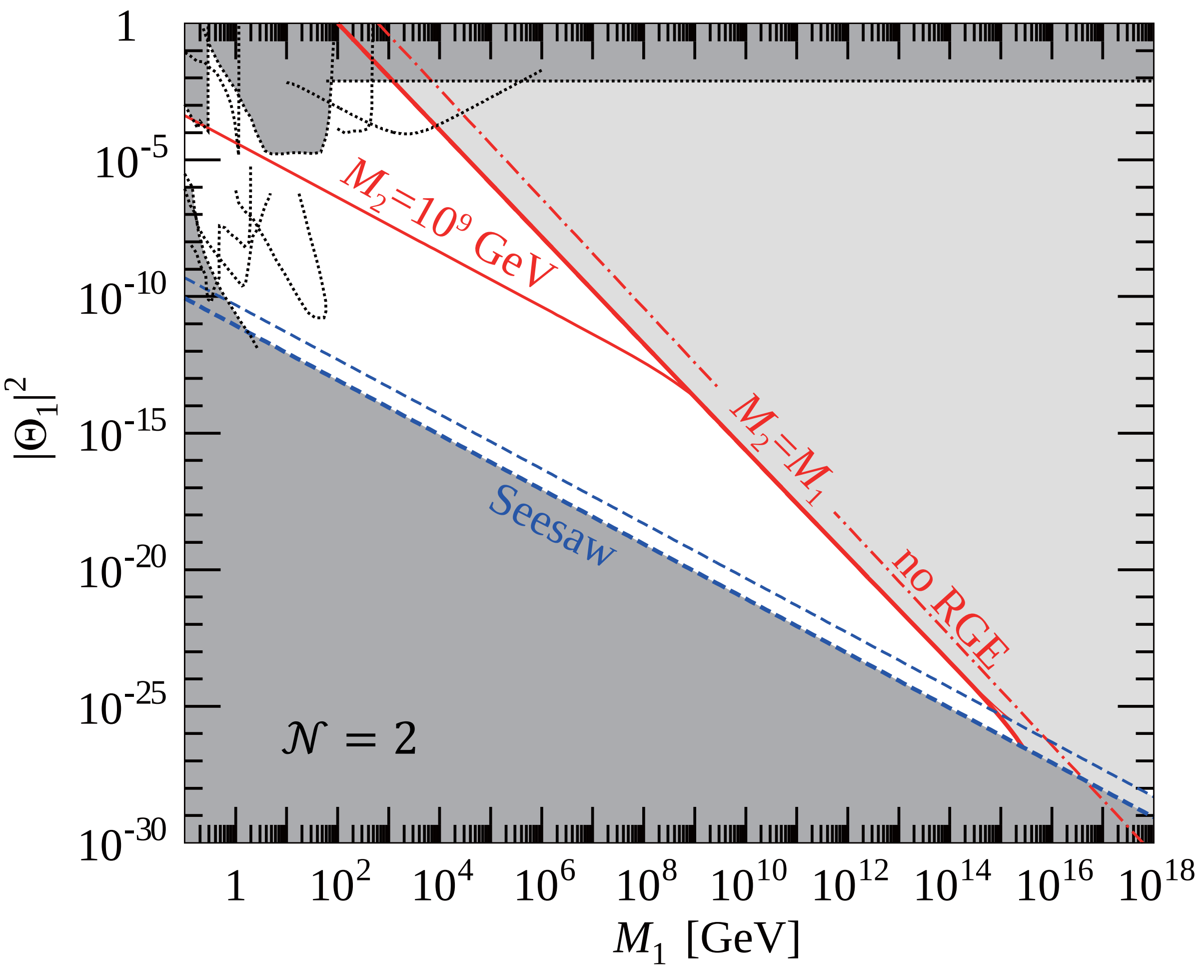
$$|F_{\alpha 2}|^2 = \frac{M_2^2}{\langle \Phi \rangle^2} |\Theta_{\alpha 2}|^2$$

- Perturbativity gives the upper bound on the mixing

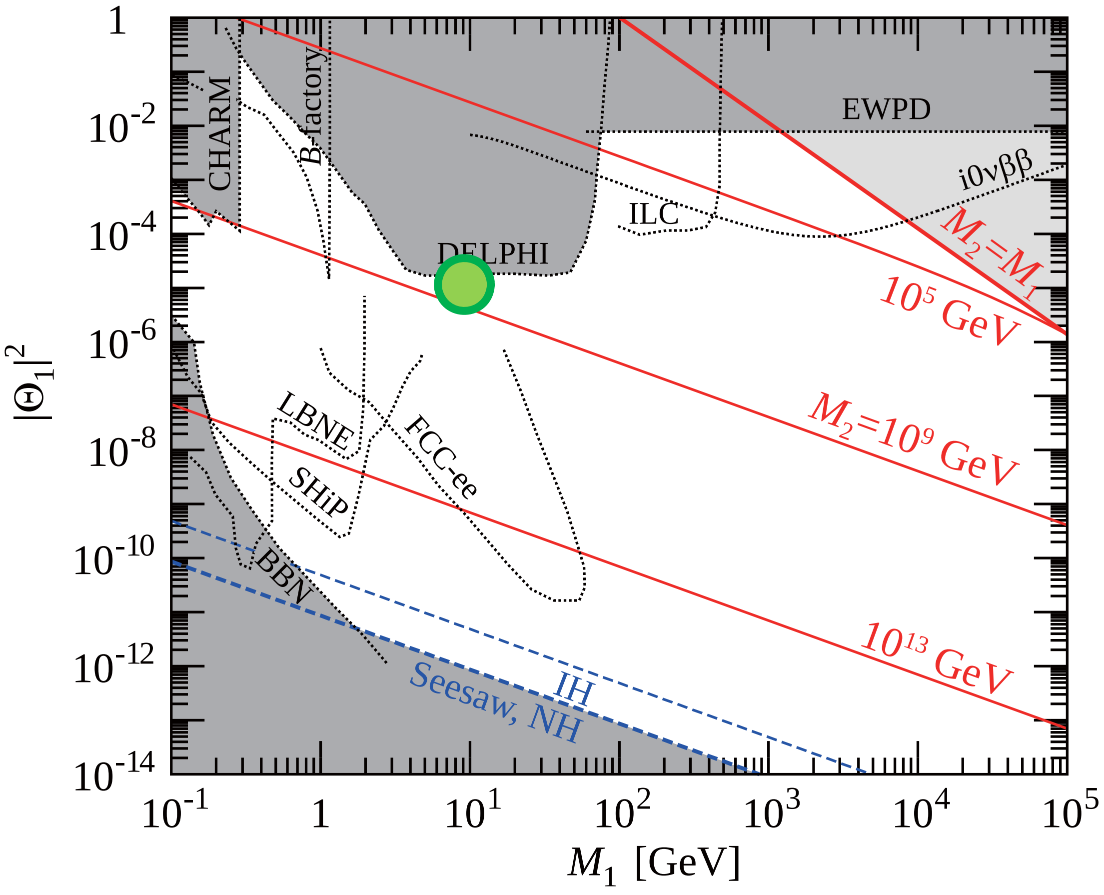
$$\boxed{|\Theta_{\alpha 1}|^2 \leq \sum_{I=2}^{\mathcal{N}} |\Theta_{\alpha I}|^2 \frac{M_I}{M_1} = \sum_{I=2}^{\mathcal{N}} \frac{|F_{\alpha I}|^2 \langle \Phi \rangle^2}{M_1 M_I} \leq \frac{4\pi(\mathcal{N}-1)\langle \Phi \rangle^2}{M_1\, M_2}}$$

Perturbativity in the seesaw mechanism

- Upper bound on mixing



Implication to high energy phenomena



If HNL N_1 with $M_1 \sim 10$ GeV and $|\Theta_1|^2 \sim 10^{-5}$ is discovered, perturbativity requires $M_2 < 10^9$ GeV !

Leptogenesis is disfavored !

HNL searches at low energy can probe high energy phenomena such as leptognesis !

Summary

Summary

- Right-handed neutrinos are well-motivated physics beyond the Standard Model

- They can explain neutrino masses through the seesaw mechanism and baryon asymmetry of the universe (BAU) (via leptogenesis, neutrino oscillation, ···) at the same time.

- Experimental tests of such right-handed neutrinos are important to understand the origin of neutrino masses and BAU